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New Course in Industrial Engineering Education Curriculum

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Abstract

Industrial engineering degree curriculum has many courses, supply chain management, production planning and so on. However there is need to introduce new course in industrial engineering degree curriculum, creative industrial engineering. This course will apply industrial engineering in a creative way. At the end of day, industrial engineering is about optimisation and optimisation can be done in a creative way. Such an Industrial Engineering is also Down to Earth. Such an Industrial Engineering is creative. In that it generates ideas that have not been thought before. Creativity is defined as generating something new and original. This course will be designed by industrial engineering teachers who have taken extensive and intensive training in creative thinking, design thinking, lateral thinking etc. They will apply the principles learnt in creative thinking, design thinking and lateral thinking to the problems of industrial engineering.

Keywords: Industrial engineering, Creativity, Education.

1 | Introduction

The author has submitted several papers to sister journal of this publication - Industrial Engineering. However since this paper, which related to Industrial Engineering is related to Education, hence is being submitted to Education Journal.

In the papers submitted to Industrial Engineering journal, the author has suggested a Revolution in Industrial Engineering. The author has suggested that Industrial Engineering has to become more down to earth and commonsensical.

Author has also suggested that Industrial Engineering has to be viewed as a mindset - a way of thinking - instead of as a methodology - set of methods. Author has also suggested that Industrial Engineering has to become more creative with elements of lateral thinking, divergent thinking, brainstorming, right brain thinking, out of box thinking and so on.

This paper taking off from the papers submitted to Industrial engineering journal would like to introduce a new course in Industrial Engineering education curriculum.

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2 | What is Industrial Engineering?

Here is definition of engineering. Engineering is application of science and mathematical models to the innovation, design, construction and maintenance of structures, machines, materials, devices, systems, processes and organisations. And here is definition of industrial engineering.

Industrial engineering is optimisation of complex processes, systems and organisations by developing, improving and implementing systems of people, money, knowledge, information and equipment [1]-[7].

Basically, industrial engineering seems to be some sort of specialisation in engineering with focus on optimisation. And optimisation means making best use of something.

Industrial engineering is thus a set of mathematical and scientific methods geared for optimisation through improving and implementing money, machine and material [8]-[15].

In most industrial engineering education curriculum, apart from general courses there are various subjects such as:

I. Work system design.
II. Quality engineering and management.
III. Supply chain management.
IV. Facilities and layout planning.
V. Procurement and materials management.
VI. Operations research.
VII. Human factor engineering.
VIII. Project management.

3 | Creative Industrial Engineering

However there is need to introduce a new course in industrial engineering curriculum. It will be called creative industrial engineering. This course will apply industrial engineering in a creative way. After all let us go back to that definition of industrial engineering. At the end of day, industrial engineering is about optimisation. And optimisation can be done in a creative way. After all the easiest example one can think of for optimisation in a common sense way is Traffic Jam Solution. Obviously if you replace cars by buses then 90% of traffic space will be reduce. That is common sense industrial engineering.

Such an Industrial Engineering is also Down to Earth. Meaning this branch of industrial engineering applies itself to situations for common people and not necessarily multinational technological corporates. These could be issues of reducing congestion in crowded trains in Mumbai by say reducing number of seats and thus increasing standing space.

Such an industrial engineering is creative. In that it generates ideas that have not been thought before. Creativity is defined as generating something new and original. Such an industrial engineering also operates through divergent thinking. This means generating as many ideas as possible in free thinking way rather than conditioned way.

Again this sort of industrial engineering steps down from Ivory Tower of Academic World and applies itself to ordinary situation in an ordinary way. Again this sort of industrial engineering steps out of comfort zone of factory, office and retain and applies itself to ordinary situations.

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4 | National Institute of Training in Industrial Engineering

Let us discuss the above idea in a greater detail. While other nations have engineering colleges, medical colleges, management colleges. India has an entire college devoted to industrial engineering. It is called National Institute of Training in Industrial Engineering (NITIE).

As is obvious from the name the institute is dedicated and devoted to education and research and development in area of Industrial Engineering. The institute takes students at post graduate level and has three major programs:

I. Post Graduate Diploma in Industrial Management (PGDIM).
II. Post Graduate Diploma in Systems Management (PGDSM) and finally the diploma program in industrial engineering.
III. Post Graduate Diploma in Industrial Engineering (PGDIE).

The post graduate diploma in industrial engineering course has four components:

– *Institute core.*
– *Program core.*
– *Program electives.*
– *Institute electives.*

Institute core consist of following courses:

I. Industrial engineering and productivity management.
II. Operations management.
III. Managerial economics.
IV. Marketing management.
V. Business communication.
VI. Quantitative techniques.
VII. Managerial accounting.
VIII. Organisation behaviour.
IX. Information systems and artificial intelligence.
X. Technology and innovation management.
XI. Sustainable development for business.
XII. Legal and ethical aspect for business.

The program electives have following courses in various modules such as:

1. Industrial engineering and manufacturing systems module which has following courses:

– *Manufacturing planning and control.*
– *Computer integrated manufacturing.*
– *Flexible manufacting systems.*
– *Fuzzy logic industrial engineering.*
– *Global and collaborative manufacturing.*
– *Lean manufacturing.*
– *Maintenance management.*
– *Manufacturing strategy.*
– *Manufacturing system design.*
– *Manufacturing system and service.*
– *Additive manufacturing.*
– *Ergonomics assessment tools.*

- *Ergonomics in manufacturing.*
- *Simulation modeling and analysis.*
- *Systems modeling.*
- *Intelligent optimization.*
- *Reliability engineering.*

Other modules are:

- *Operations and supply chain management.*
- *Decisions science and information system.*
- *Engineering technology and project management.*

Each of these modules has several courses; but it is not within scope of this paper to discuss them. Apart from this there are institute electives. The program also has considerable project work and reseach component to it. One intends to introduce another core course in Institute core course. This course will be called creative industrial engineering.

5 | Detailed Look at Creative Industrial Engineering

This program will have several components follow as:

Out of box thinking

Thinking out of box means to think differently, from a new perspective and unconventionally. Industrial engineering should adopt creative thinking approach and step out of the box, or the edges to be able to think differently. Usually humans are trained within what they assume to be constraints and boundaries. However it is possible that a more optimum solution to a problem exists outside the boundaries.

Einstein said that "insanity means doing same thing over and over again expecting different results". That is starting point of out of box thinking. Instead of doing same thing why not step outside the familiar and view the problem in different light. Industrial engineering must adopt out of box thinking.

Lateral thinking

Linear thinking means thinking where designers approach the problem by using reasoning that is disruptive and not immediately obvious. Lateral thinking is also called horizontal thinking. Most problems are approach through Linear thinking also called vertical thinking through mathematical and analytical and scientific and structured step by step approach.

Industrial engineering as it exists today operates from linear thinking or vertical thinking, which is mathematical, scientific and analytical. Industrial engineering has to think in a lateral fashion in a way that is creative, innovative and disruptive, which is also described as horizontal thinking.

Right brain thinking

There is a thought process that believes that Right Brain is creative, intuitive, artistic, imaginative, musical and emotional. Whereas left brain is logical, analytical, mathematical, verbal, sequential and factual. This comes from work of Roger Sperry who was awarded Nobel Prize.

Now conventional Industrial Engineering it should be obvious operates out of Left Brain, in that it is full of logical attitudes and mathematical procedures. However Industrial Engineering must start to be more right brained and have intuitive, imaginative, artistic component to it.

Divergent thinking

Divergent thinking is a method used to generate creative ideas by exploring many solutions. It occurs in a free flowing, spontaneous and non linear manner. Convergent thinking occurs where there is single solution arrived at by established procedure.

Industrial engineering as it stands today operates out of convergent thinking. There is need to explore if industrial engineering can operate out of divergent thinking by generating many possible solutions.

Creative thinking

Creative thinking is intentionally generating new ideas from existing information. Creative thinking involves thinking in a different way and examining information from different points of view. Industrial engineering needs to explore creative thinking for it to become more effective and applicable to wider variety of situations.

Thus industrial engineering needs to explore divergent thinking, out of box thinking, creative thinking, lateral thinking and right brain thinking for it to become more effective and comprehensive.

Brain storming industrial engineering

Brain storming is a group creativity technique by which efforts are made to find conclusion to a problem by gathering a list of ideas spontaneously contributed to by members. Brainstorming is a situation where a group of people meet to generate ideas and solution around a specific domain by removing inhibitions. People are allowed to think freely and suggest as many new ideas as possible. These ideas are noted without criticism and after brain storming ideas are evaluated.

6 | Examples of Creative Industrial Engineering

Let us examine some instances of Creative industrial engineering. Take the case of Crowded Trains in Mumbai. How do we optimise the crowd in trains so that journey becomes comfortable?

Here are some ideas on how to apply optimisation:

I. Move offices to other side of town.
II. Make peak hour travel expensive.
III. Redesign seating spaces in trains.
IV. Work from home.
V. Rotate holidays.
VI. Flexible timings.
VII. Double decker trains.

This is one application of creative industrial engineering.

Let us now apply Brain Storming industrial engineering to academics. How does one optimise stress levels in academic system? How does one reduce learning hours in an academic year? How does one maximize learning? Many ideas from creative industrial engineering come to mind. Such as:

I. Have 4 days holidays before each exam. So that stress moves to 1 month of exams rather than entire semester.
II. Do no have Mid Semester exams. Instead have a quiz at end of every lecture. So that you can have continuous evaluation without associated stress.
III. Require students to summarize a text book. This will add to learning without adding to exam stress.

This is good example of creative industrial engineering applied to academics. Such approach can be applied to political campaigning too.

Can we make political campaigning more efficient and optimium? Here are some ideas:

I. Don't have political speeches. Anyway they reach barely 1% of population.
II. Have press conferences. Newspapers are read by 100% of audience.
III. Use Whatsapp and social media.
IV. Have honest politicians for a change.
V. Use reduced election expenditure as a proof of honesty and goodness.

7 | Conclusion

This course will be designed by industrial engineering teachers who have taken extensive and intensive training in creative thinking, design thinking, lateral thinking etc. They will apply the principles learnt in creative thinking, design thinking and lateral thinking to the problems of industrial engineering.

It is high time we introduce creative industrial engineering so that industrial engineering can apply itself to problems not conventionally considered as part of industrial engineering.

This will make industrial engineering step out of its comfort zone and get into down to earth commonsense problems faced by every one and provide solutions that require lateral thinking, creative thinking, out of box thinking, divergent thinking, right brain thinking etc.

The course content can differ from each institute to another teaching industrial engineering. There has to be a greater discussion amoung academicians of the feasibility of this course, since its need is without doubt unquestionable.

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Paper Type: Research Paper

Production Scheduling of Parallel Identical Lines in a Multi-Product Manufacturing System with Genetic Algorithm

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Abstract

A multi-product system is one of the different manufacturing systems in which many products have been produced that complement each other and have interdependence. These types of systems have recently been widely used in various industries. In some types of multi-product manufacturing industries that offer their products as a package, the scheduling of the production of components of each package affects the time it takes to complete the package. Therefore, a new problem has been defined that the primary purpose of its production scheduling, in addition to reducing the completion time of the products, is to make various items forming a package, get ready over a short interval of time, and be supplied to the sales unit so that the package can be delivered to the final consumer. This paper aims to express the problem of production scheduling of multi-product production systems in the form of linear programming. For this purpose, two mathematical models are presented, and their functions are compared. Besides, an efficient genetic algorithm is proposed to solve the problem, which is able to solve the problem in a reasonable time with acceptable accuracy.

Keywords: Parallel lines production scheduling, Operations sequence, Mixed-integer linear programming, Genetic algorithm.

1 | Introduction

Production planning is a branch of science that focuses on planning and scheduling productions at different levels of decision-making. Production planning has long been the subject of many studies to increase productivity in manufacturing systems. The problem of scheduling and sequencing of the operations is a branch of production planning that allocates any activity to the machine or the production line at the right time and determines the best possible sequencing of activities on machines or production lines. Various objectives have already been defined in these types of problems, each of which has been identified and resolved according to a specific need.

The production scheduling problem basically consists of the selection of a set of tasks to be performed and the construction of a schedule complying with the technological requirements and satisfying as much as possible the given demands for a final production [1]. With the global economy's rapid development, the manufacturing industry's production model has changed [2]. The

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real-life production scheduling problems may encompass many specific technological and business requirements such as due dates, sequence-dependent changeovers, unit blockages, etc. [3].

A multi-product system is one of the different manufacturing systems in which many products have been produced that complement each other and have interdependence. These types of systems have recently been widely used in various industries.

In recent years, some types of multi-product manufacturing industries, including the ceramic tile industry, have offered their products as packages. The components of each package have their own production schedule. The completion times of these components may directly affect the appropriate management of the supply chain, customer satisfaction, etc. Therefore, a new problem has been defined that the primary purpose of its production scheduling, in addition to reducing the completion time of the products, is to make various items forming a package, get ready over a short interval of time, and to supplied to the sales unit so that the package can be delivered to the final consumer.

In this paper, we attempt to express such a problem in the form of a linear programming problem and solve it. Therefore, two mathematical models are built that, unlike the usual procedure in the literature, the objective function of both models is to reduce the weighted sum of the time intervals between the various products of each package. Both models take into account the general state of n production lines and m products (jobs), and the relevant constraints on reality are developed in the models. To our knowledge, this is the first study that considers this objective function for a real-world problem and would be the paper's most important contribution. Besides, since it is impossible to solve either of the two proposed models for large-scale problems precisely in a meaningful time, an efficient genetic algorithm is proposed to solve the problem logically.

2 | Literature Review

Parallel machines' scheduling has been the subject of several pieces of research over the years, and each has added a new dimension to the problem, depending on its intended application. Considering setup times/costs [4]-[8], [17], [24], cost of earliness/tardiness [4]-[6], [12], [15], [17]-[19], [24], and machines availability [9], [10] are the examples of various issues that gradually have applied in the formulation of the problem.

Kim et al. [4] focused on the scheduling problem of identical parallel machines to minimize total tardiness. At the same time, there are Sequence-Dependent Setup Times (SDST) between the jobs with different part types. They presented a mathematical model with two encoding schemes for meta-heuristic solutions and three decoding methods for obtaining a schedule from the meta-heuristic solutions. They developed six different Simulated Annealings (SA) and genetic algorithms, with six combinations of two encoding schemes and three decoding methods. They then performed computational experiments to find the best combination. Their suggested algorithm provided better solution quality with less computation time than commercial optimization solvers.

With the same objective, Zhu and Heady [5] developed a mixed-integer programming formulation to minimize job Earliness and Tardiness (ET) in a multi-machine scheduling problem, which considers setup times for the jobs, due dates, and also cost penalties. At the same time, the characteristics of the machines are not uniform. Also, Omar and Teo [6] studied the problem of identical parallel machine scheduling with specific due dates and early due date restrictions. They developed a mixed-integer programming model to tackle such problems. The objective is to minimize the sum of earliness/tardiness in the presence of setups.

Lee et al. [7] considered the scheduling problem of two identical parallel machines with multi-attribute setup times, while each job has some attributes, and each attribute has several different levels. The objective is to minimize the makespan. They presented a heuristic and a Variable Neighborhood Search

(VNS) metaheuristic. Also, Heydari and Aazami [8] developed a two-objective model to solve job shop scheduling problems with SDST when the aim is to optimize both objectives (makespan and maximum tardiness) simultaneously. They utilized the ε-constraint method to solve the model. A set of generated numerical data validates the model's efficiency and flexibility.

Wang and Cheng [9] investigated a problem of two identical parallel machine scheduling, in which one machine is available for processing jobs in a limited time interval. In contrast, the other machine is always available over the scheduling horizon. The objective is to maximize the number of on-time jobs. They also developed a heuristic to deal with the problem. Liao and Sheen [10] studied the scheduling problem of identical machines considering machine availability and eligibility constraints to minimize the makespan. In contrast, the machines are not continuously available at all times, and each job can only be processed on specified machines. A network flow approach is utilized to formulate the problem into a series of maximum flow problems. They proposed a polynomial-time binary search algorithm to verify the infeasibility of the problem or find the optimal solution if a feasible schedule exists.

Jia et al. [11] studied the scheduling problem of parallel batch machines with arbitrary capacities, where the non-identical-size jobs have identical processing times and unequal weights. After being processed, the jobs are delivered to the customers by some vehicles. The objective is to minimize the total weighted delivery time of all jobs. To solve the problem, they presented two heuristic algorithms, developed an algorithm based on ant colony optimization, and compared their performance.

Tavakkoli-Moghaddam et al. [12] presented a new mathematical model for a multi-criteria parallel machine scheduling problem to minimize the total earliness, tardiness penalties, and machine costs. They proposed a metaheuristic method based on the genetic algorithm and represented computational results.

Cheng et al. [13] considered parallel batch processing machines scheduling problems, where the job sizes are non-identical and are processed in batches, and the machines' capacities are the same. Using a mixed-integer programming method, they presented models for minimizing makespan and total completion time and then provided a polynomial time algorithm for minimizing the two objectives. Different-scale random instances were used to test the effectiveness of the proposed algorithm. In a similar study, Muter [14] investigated the scheduling problem of single and parallel batch processing machines to minimize makespan and presented a reformulation for the scheduling of parallel batch processing machines, which is based on decomposition in two levels, and proposed an exact algorithm to solve it. Mirmohseni et al. [15] developed a dynamic programming framework for minimizing total tardiness for sequencing weighted jobs on a single machine. Fuzzy numbers were utilized to cope with the uncertainty.

Shabtay et al. [16] studied a single-machine scheduling problem, where there exists an expected due date for all jobs to minimize the objective function, including job-dependent penalties due to early and late work. Then they provided a pseudo-polynomial time algorithm to solve the problem and studied two particular cases that are solvable in polynomial time. Rafiei et al. [17] presented a mathematical model for optimizing multi-product single-machine scheduling problems when a considerable percentage of available production times is allocated to machine setup times. The model considers sequence-dependent setup costs, costs of delays in deliveries, holding costs, and costs of idle times. The objective is to minimize the total production time, earliness, and tardiness times. Random small-size test cases are defined and solved.

In recent years, some new topics have been considered. Considering energy consumption is one of these new topics [18]-[21]. In addition, several pieces of research have studied the integration of production scheduling and other subjects such as maintenance planning, distribution planning, etc. [22]-[25].

Antoniadis et al. [18] considered the problem of scheduling jobs on parallel machines with release dates, deadlines, and processing times, which aims to minimize the total energy consumed. Machines may be in one of the two states: 'sleep' or 'active'. By entering into the 'sleep' state, they consume no energy. Each machine requires L units of energy to awaken from the 'sleep' state, and by entering into its 'active' state, the machine can process jobs and consumes a unit of energy per unit of time. They provided a constant approximation algorithm for this problem.

Módos et al. [19] considered a production scheduling problem in companies with large electricity consumption, where there is one machine and release times for the operations. The objective function is to minimize total tardiness. They presented robust production schedules that guarantee that the energy consumption constraints are not violated for each given set of uncertainty scenarios. A pseudo-polynomial algorithm was proposed to find the optimal robust schedule of the given sequence of operations. Then, they utilized this algorithm in three different (two exact and one heuristic) algorithms for finding the optimal sequence.

Aghelinejad et al. [20] investigated a single-machine manufacturing system to minimize the production system's total energy costs. They presented two mathematical models to formulate such a problem and developed a heuristic and a genetic algorithm to solve the model and provide solutions in reasonable computational time. Different numerical experiments were utilized to test the effectiveness of the proposed optimization methods. The results approved the accuracy and efficiency of both algorithms.

Anghinolfi et al. [21] investigated the multi-objective combinatorial optimization problem of scheduling jobs on multiple parallel machines, while the objective is minimizing both the makespan and the total energy consumption. An ad-hoc heuristic method was developed to solve the problem.

Bhosale and Pawar [22] considered integrating production planning and scheduling. They selected a case study based on the parallel-line continuous process plant and optimized its performance by a real coded genetic algorithm. Results represent that the algorithm outperforms the solutions obtained by previous researchers.

Cui et al. [23] investigated the integration of production scheduling and maintenance planning to optimize two objectives of quality robustness and solution robustness for flow shops when the occurrence of failure is uncertain. They proposed a mathematical model to formulate the problem. They also presented a two-loop algorithm that optimizes the sequence of jobs, positions of preventive maintenance, and idle times. Computational results approved the performance of the proposed algorithm. Also, Chansombat et al. [24] also utilized mixed-integer linear programming and presented a model that simultaneously solves the integrated production and preventive maintenance scheduling problem in the capital goods industry. The objective was to minimize total costs, including earliness/ tardiness penalty costs, component and assembly holding costs, preventive maintenance costs, and the costs of setup, production, transfer, and production idle time. They tested the model using real data. The results show that the total cost may be reduced to 63.5%.

Furthermore, Devapriya et al. [25] focused on the integrated production and distribution scheduling problem of a perishable product that its production and distribution must be done before it becomes unusable. Minimizing the costs is considered when the product has a limited lifetime, and the total demand must be satisfied within the planning horizon. They presented a mixed-integer programming model to solve the problem, then provided heuristics based on evolutionary algorithms to resolve the model. Sifaleras et al. [26] proposed a mathematical production-planning model for a real-world production optimization problem of a non-alcoholic soft drinks company in Northern Greece. The model's objective is to minimize the company's idle human-hours subject to fulfilling customers' demands. Then they solve the model using Python and Gurobi solver.

Various objectives have been considered in the formulation of production schedules all over the world. Many of them studied minimizing the makespan. Others applied to minimize (total) costs, total completion time, total earliness and/or tardiness, total energy consumed (costs), delivery times, and maximizing the number of on-time jobs. To the best of our effort, minimizing the time intervals between

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the completion times of different items of each package has not been studied before. Therefore, since several industries use multi-product systems, it requires a comprehensive study.

3 | Problem Statement

The research problem is determining the sequence and scheduling of producing the products offered in a product package. Each product package consists of some products; each has its own processing time and limitations; e.g., in a ceramic tile factory, a product package may include various components, such as floor tiles, wall tiles, decors, borders, etc. The goal is to schedule the production such that reducing product completion times minimizes the difference between the completion times of the first product and the final product in each package. In the literature, frequently minimizing the makespan has been considered the objective, which does not apply to this research.

3.1 | Definitions and Assumptions

The general state of n production lines and m jobs is considered. We define the first product of the first package as job 1, the second product of the first package as job 2,… and the final product of the last package as job m.

The following concepts are assumed in modeling the general state of the problem:

I. Production lines are identical, and each one is able to do all the jobs.
II. Preemption is not permitted; i.e., assigning one job to one line requires the whole job to be done on the same line, and part of the job is not entitled to transfer to another line. It is also not allowed to interrupt and perform part of it at another time.
III. Setup times for all products on all lines are negligible.
IV. Each line is capable of doing one job at a time.
V. Each job may be replaced with another job on each line (no precedence is considered).
VI. All jobs may start from time zero.
VII. All lines from time zero and during the planning horizon are continuously available and capable of operating (there is no unavailability to the lines).
VIII. The processing time of each job on each line is known.
IX. All lines have continuous production and no idle time.

4 | Mathematical Modeling

4.1 | Model 1

Some indices are used to model this problem, which we describe below.

4.1.1 | Indices used in the first model

i: line (machine) index, i = 1, 2, ..., n.

j: job index, j = 1, 2, ..., m.

k: package index, k = 1, 2, ..., o.

T_{ij}: the processing time of job j on line I.

M: a large positive number.

W_k: the importance (weight) of package k.

F_k: the set of jobs related to package k.

4.1.2 | Decision variables

In this linear integer model, six types of decision variables are used:

U_k: completion time of the last product of package k which gets prepared, $U_k = max \{ C_j / j \in F_k \}$.

L_k: completion time of the first product of package k which gets prepared, $L_k = min \{ C_j / j \in F_k \}$.

Y_{ij}: 1, if job j gets done on line i, otherwise 0.

$X_{ij'j}$: 1, if job j gets done immediately after job j' on line i, otherwise, 0.

X^1_{ij}: 1 if job j gets done as the first job on line i, otherwise 0.

C_j: completion time of job j.

Y_{ij}, $X_{ij'j}$ and X^1_{ij} are zero-one variables; U_k, L_k, and C_j are non-negative ones.

4.1.3 | First model

The proposed linear model is as follows:

$$\text{Min}\, Z = \sum_{k=1}^{O} W_k.\ \ U_k - L_k), \tag{1}$$

s. t.

$$\sum_{i=1}^{n} Y_{ij} = 1 \quad \text{for a all } j, \tag{2}$$

$$C_j \leq X^1_{ij} . T_{ij} + M\left(1 - X^1_{ij}\right) \quad \text{for all } i, j, \tag{3}$$

$$C_j \geq X^1_{ij} . T_{ij} - M\left(1 - X^1_{ij}\right) \quad \text{for all } i, j \tag{4}$$

$$C_j \leq C_{j'} + X_{ij'j} . T_{ij} + M\left(1 - X_{ij'j}\right) \quad \text{for all } i, j, j', j \neq j', \tag{5}$$

$$C_j \geq C_{j'} + X_{ij'j} . T_{ij} - M\left(1 - X_{ij'j}\right) \quad \text{for all } i, j, j', j \neq j', \tag{6}$$

$$\sum_{i=1}^{n} \sum_{\substack{j'=1 \\ j' \neq j}}^{m} X_{ij'j} + \sum_{i=1}^{n} X^1_{ij} = 1 \quad \text{for all } j, \tag{7}$$

$$\sum_{\substack{j'=1 \\ j' \neq j}}^{m} X_{ij'j} + X^1_{ij} = Y_{ij} \quad \text{for all } i, j, \tag{8}$$

$$\sum_{\substack{j=1 \\ j \neq j'}}^{m} X_{ij'j} \leq Y_{ij'} \quad \text{for all } i, j', \tag{9}$$

$$\sum_{j=1}^{m} X^1_{ij} = 1 \quad \text{for all } i, \tag{10}$$

$$L_K \leq C_j \quad \text{for all } K,\ j \in F_K, \tag{11}$$

$$U_K \geq C_j \quad \text{for all } K,\ j \in F_K, \tag{12}$$

$$U_K, L_K, C_j, \geq 0 \quad \text{for all } K, j, \tag{13}$$

$$Y_{ij}, X_{ij'j}, X^1_{ij} = 0{,}1 \quad \text{for all } i, j, j'. \tag{14}$$

Eq. (1) represents the objective function of the problem. As stated, the purpose is to determine the production sequence of different products on different lines so that the least possible time interval would exist between the completion times of various items of each package.

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Eq. (2) ensures that each job is only performed on a single line. *Eqs. (3)* to *(6)* indicate the completion times of different items and guarantee that idle time does not occur on the lines. *Eq.s (3)* and *(4)* guarantees that each line's first job begins at zero. *Eqs. (5)* and *(6)* guarantees no idle time between each job and its previous one. *Eq. (7)* ensures that none of the lines' jobs will have more than one position and will not be placed on more than one line (only has one position on all lines). *Eq. (8)* ensures that none of the lines' jobs will be placed after more than one job. *Eq. (9)* ensures that none of the lines' jobs will be placed before more than one job. *Eq. (10)* ensures that no more than one job will be identified as the first on any of the lines. *Eqs. (11)* and *(12)* define the decision variables U_k and L_k that to include these variables in the linear programming problem, *Eqs. (11)* and *(12)* have been added to the model. *Eqs. (13)* and *(14)* indicate the types of decision variables.

The number of decision variables in this model equals to: $\{(i.j)\ (j+1)+2k+j\}$. The number of constraints in this model equals:

$$\{(i.j)\ (2j+1)+i\,(j-1)+4j+i\} \text{ or } \{i \times (j-1)\ (2j+1)+3\,(i.j)+4j+i\}.$$

4.2 | Model 2

While both models give the same solutions ultimately, their mechanisms are different in determining the optimal solution. The first model specifies that each task should be performed after which task and on which line (without specifying the position number of that task), while the second model only specifies the position number of each task on each of the lines (without specifying the tasks before and after it).

4.2.1 | Indices used in the second model

i: Line (machine) index, $i=1, 2, ..., n$.

j: Job index, $j=1, 2, ..., m$.

f: Position number index, $f=1, 2, ..., m$.

k: Package index, $k=1, 2, ..., o$.

T_{ij}: The processing time of job j on line I.

M: A large positive number.

W_k: The importance (weight) of package k.

F_k: The set of jobs, related to package k.

4.2.2 | Decision variables

In this linear integer model, five types of decision variables are used:

U_k: Completion time of the last product of package k which gets prepared, $U_k = max\ \{C_j\ /j \in F_k\ \}$.

L_k: Completion time of the first product of package k which gets prepared, $L_k = min\ \{C_j\ /j \in F_k\ \}$.

Y_{ij}: 1, if job j gets done on line i, otherwise 0.

$X^f{}_{ij}$: 1 if job j gets done as the f[th] job on line i, otherwise 0.

C_j: Completion time of job j.

Y_{ij} and $X^f{}_{ij}$ are zero-one variables; U_k, L_k, and C_j are non-negative ones.

4.2.3 | Second model

The proposed linear model is as follows:

$$\text{Min}\, Z = \sum_{k=1}^{O} W_k \quad U_k - L_k \,), \tag{15}$$

s. t.

$$\sum_{i=1}^{n} Y_{ij} = 1 \quad \text{for all j}, \tag{16}$$

$$C_j \leq T_{ij} + M\left(1 - X^1{}_{ij}\right) \quad \text{for all i,j}, \tag{17}$$

$$C_j \geq T_{ij} - M\left(1 - X^1{}_{ij}\right) \quad \text{for all i,j}, \tag{18}$$

$$C_j \leq C_{j'} + T_{ij} + M\left(1 - X^f{}_{ij}\right) + M\left(1 - X^{f-1}{}_{ij'}\right), \quad \text{for all i,j,j}',\text{f}, \ j \neq j', f \neq 1, \tag{19}$$

$$C_j \geq C_{j'} + T_{ij} - M\left(1 - X^f{}_{ij}\right) - M\left(1 - X^{f-1}{}_{ij'}\right), \quad \text{for all i,j,j}',\text{f}, \ j \neq j', f \neq 1, \tag{20}$$

$$\sum_{i=1}^{n} \sum_{f=1}^{m} X^f{}_{ij} = 1 \quad \text{for all j}, \tag{21}$$

$$\sum_{j=1}^{m} X^f{}_{ij} \leq 1 \quad \text{for all i,f}, \tag{22}$$

$$\sum_{f=1}^{m} X^f{}_{ij} = Y_{ij} \quad \text{for all i,j}, \tag{23}$$

$$\sum_{j=1}^{m} X^f{}_{ij} \leq \sum_{j'=1}^{m} X^{f-1}{}_{ij'} \quad \text{for all i}, f \neq 1, \tag{24}$$

$$L_k \leq C_j \quad \text{for all } k, \quad j \in F_k, \tag{25}$$

$$U_k \geq C_j \quad \text{for all } k, \quad j \in F_k, \tag{26}$$

$$U_k, L_k, C_j \geq 0 \quad \text{for all k,j}, \tag{27}$$

$$Y_{ij}, X^f{}_{ij} = 0,1 \quad \text{for all i,j,f}. \tag{28}$$

Eq. (15) represents the objective function of the problem, which is the same as the objective function of the first model. *Eq. (16)* ensures that each job is only performed on a single line. *Eqs. (17)-(20)* indicate the completion times of different items and guarantee that idle time does not occur on the lines. *Eqs. (17)* and *(18)* guarantees that each line's first job begins at zero. *Eqs. (19)* and *(20)* guarantees no idle time between each job and its previous one. *Eq. (21)* ensures that none of the lines' jobs will have more than one position and will not be placed on more than one line (only has one position on all lines). *Eq. (22)* ensures that none of the lines' positions (f indices) will be assigned to more than one job. *Eq. (23)* ensures that if one job is done on one line, it has precisely one position on that line. *Eq. (24)* ensures that no position is assigned on any lines until its preceding position is assigned. *Eqs. (25)* and *(26)* define the decision variables U_k and L_k that to include these variables in the linear programming problem, *Eqs. (25)* and *(26)* have been added to the model. *Eqs. (27)* and *(28)* indicate the types of decision variables.

The number of decision variables in this model equals to: (i.j) (f + 1) + 2k + j. The number of constraints in this model equals to: (i.j) (2 (j-1). (f-1) + 3) + i (2f-1) + 4j.

5 | Genetic Algorithm

Genetic algorithm is a global search technique based on natural genetic concepts and is one of the most widely used meta-heuristic approaches. We try to solve the stated problem utilizing the GA.

5.1 | Answer Representation

To represent the chromosomes, we use the structure presented in *Fig. 1*. Each chromosome contains i + j-1 genes that the numbers 1, 2, ..., j are the jobs indicators, and i-1 numbers from j + 1 onward, placed in the genes, each one indicates a change in producing line. An example of a sequence of genes in a chromosome on two lines is shown in the following figure:

Machine 1: 1, 2, 3, 4								
Machine 2: 5, 6, 7, 8								
8	7	6	5	9	4	3	2	1

Fig. 1. Chromosomes representation.

5.2 | Generation of an initial population

To get faster access to the optimal answer, a condition was considered for selecting the initial population:

First, one package is selected randomly, then the jobs related to that package are chosen randomly and randomly assigned to one of the lines. After completing the jobs of that package, the following package is selected randomly, and this process is repeated until all jobs are assigned to the lines. Each chromosome is compared to all the previous chromosomes and will not be selected if it is duplicated.

For example, if there are 12 jobs in 4 packages and 2 production lines, some of the permitted combinations in the initial population are shown in *Fig. 2.*

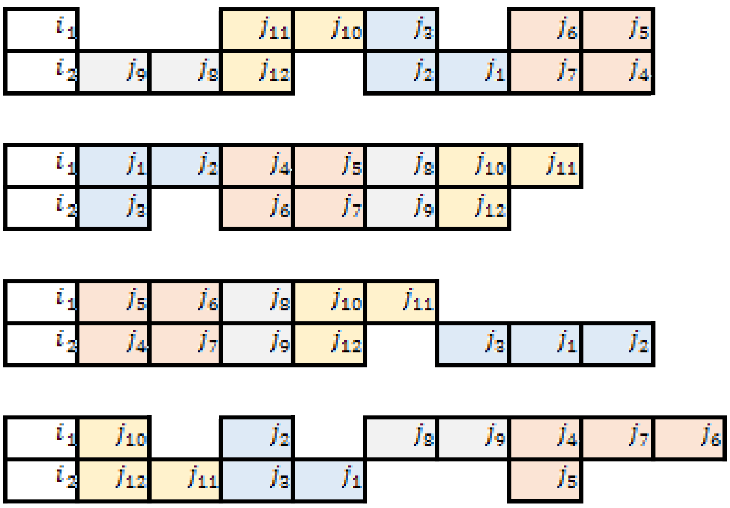

Fig. 2. Some permitted combinations in the initial population.

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5.3 | GA Operators

Selection operator

For selecting parents, we use the roulette wheel method so that by applying a coefficient (selection pressure) for each chromosome, a modified fitness function will be defined, and based on that, chromosomes will be ranked. Then, each chromosome will be assigned a probability (a fraction of the accumulation probability of the chromosomes). Finally, two non-same chromosomes will be selected randomly as the parents.

Crossover operator

The generation of offspring is performed by a particular single-point crossover operator designed below.

First, a random number is generated over the interval (the length of the chromosome), then as many as the generated random number, the genes of the first parent are repeated in the first offspring. Its remaining genes are arranged in the following order of placement in the second parent chromosome. Contrary to the above procedure will be done for generating the second offspring.

Mutation operator

Two genes of the parent's chromosome are randomly selected and replaced, called mutants population.

5.4 | Formation of the Next Generation

In order to resume the algorithm to the next generation, 30% of the elites of the previous generation will be transferred to the next generation. Then, 40% of the offspring produced by the intersection operator, 5% of the mutant population, and the rest of the population of the previous generation will be considered, and up to 70% of the size of the population will be chosen randomly among them and transferred to the next generation.

5.5 | Stopping Rule

Two conditions for stopping the algorithm are considered. If the algorithm meets each one, then it will stop, and the results will be announced. These two conditions are:

I. Producing 500 generations.
II. No change in the best value obtained from the fitness function for 200 consecutive generations.

6 | Solving Numerical Examples

To determine the efficiency of the proposed solution method, we will compare three small and modest size numerical examples, and the obtained objective function value, as well as the solution time, will be compared for the two proposed models and the proposed algorithm. To solve the models, the software GAMS 24.8.5 (r61358) and to solve the genetic algorithm, MATLAB R2015 (8.5.0.197613), was used on the laptop with Intel® Core ™ i3 processor and 1066 MHz DDR3 memory SDRAM.

i = 1, 2; j = 1, 2, 3, 4, 5, 6; k = 1, 2, 3;

f(k)	j=1	j=2	j=3	j=4	j=5	j=6
k=1	*	*				
k=2			*	*		
k=3					*	*

W(1) = W(2) = W(3) = 1

T_{ij}	j=1	j=2	j=3	j=4	j=5	j=6
i=1	3	5	5	4	4	5
i=2	3	4	6	2	5	6

Comparison of answers of example 1				
	Objective function	Lower bound	Gap (%)	Solution time (s)
First model	2	2	0	0.31
Second model	2	2	0	1.76
The proposed GA (average of 50 trials)	2	2	0	2.65

Fig. 3. Example 1.

i = 1, 2; j = 1, 2, 3, 4, 5, 6, 7, 8; k = 1, 2, 3, 4;

f(k)	j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8
k=1	*	*						
k=2			*	*				
k=3					*	*		
k=4							*	*

W(1) = W(2) = W(3) = W(4) = 1

T_{ij}	j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8
i=1	3	5	5	4	4	5	3	3
i=2	3	4	6	2	5	6	2	4

Comparison of answers of example 2				
	Objective function	Lower bound	Gap (%)	Solution time (s)
First model	3	3	0	17.91
Second model	3	3	0	90.54
The proposed GA (average of 10 trials)	3	3	0	3.07

Fig. 4. Example 2.

i = 1, 2; j = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12; k = 1, 2, 3, 4;

f(k)	j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8	j=9	j=10	j=11	j=12
k=1	*	*	*									
k=2				*	*	*	*					
k=3								*	*			
k=4										*	*	*

W(1) = W(2) = W(3) = W(4) = 1

T_{ij}	j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8	j=9	j=10	j=11	j=12
i=1	3	5	5	4	4	5	3	3	7	2	5	3
i=2	3	4	6	2	5	6	2	4	6	2	4	3

Comparison of answers of example 3				
	Objective function	Lower bound	Gap (%)	Solution time (s)
First model	8	8	0	14499.75
Second model	8	7	12.5	500000.79
The proposed GA (average of 10 trials)	8	8	0	7.37

Fig. 5. Example 3.

7 | Conclusion

In this paper, the production scheduling of multi-product manufacturing systems as one of a variety of production systems was investigated, and we tried to express such a problem in the form of a linear programming problem. For this purpose, two mathematical models were presented that, unlike the usual procedure in the literature, the objective function of both models is to reduce the sum of the time intervals between the various products of each package. Both models take into account the general state of n production lines and m products (jobs) and the relevant constraints on reality developed in the models. Besides, since it is impossible to solve either of the two proposed models for large-scale problems, precisely in a meaningful time, an efficient genetic algorithm was proposed to solve the problem logically.

Furthermore, a few simple examples were defined. The result is neither of the two models presented for large-scale problems can be solved precisely in a justifiable time. Then, the genetic algorithm was utilized to solve the problem in a reasonable time with acceptable accuracy. Comparison with the exact solutions shows the efficiency of the proposed algorithm.

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A Mathematical Model for Robust Landing and Take-Off Scheduling at an Airport Considering Runway Disturbances

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Abstract

The Aircraft Scheduling Problem (ASP) refers to allocating each aircraft to the optimal take-off and landing time and the appropriate runway. This problem is the allocation of aircraft to the desired runway so that the total damage due to delays or haste in landing or take-off of all aircraft is minimized. Runway allocation, landing and take-off sequences, and scheduling for each aircraft must be done in a predetermined time window. Time should also be considered as the time of separation between landings and take-offs due to the wake vortex phenomenon. In general, the purpose of such problems is to make maximum use of the runway. Therefore, in this study, a mathematical model of robust landing and take-off scheduling at an airport is provided, assuming no access to the airport runway at certain times. Moreover, delays and haste in landing and take-off on the runway, limited access to aircraft, runway repair time, and the possibility of runway disturbances are investigated. Robust optimization is used to deal with uncertainty at take-off and landing times. Finally, Genetic and Imperialistic Competitive Algorithm (ICA) are used to evaluate and analyze the problem because it is NP-HARD problem. The results indicate the ability of the proposed algorithms to find high-quality solutions in a short computation time for problems up to 7 runways and 60 aircraft.

Keywords: Aircraft scheduling problem, Robust optimization, Genetic algorithm, Imperialistic competitive algorithm.

1 | Introduction

Nowadays the high volume of transportation is done by aircraft (plane), which is very expensive compared to other transportation systems. Some of these costs include damages due to delays and haste in landing and flight, which include significant figures, so saving them leads to a significant reduction in total costs. Therefore, special importance is given to the optimal landing and take-off scheduling. Rising fuel prices have made this even more important. This problem is the allocation of aircraft to the desired runway so that the total damage due to delays or haste in landing or take-off of all aircraft is minimized. In general, the purpose of such problems is to make maximum use of the runway.

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Air transportation plays a significant role in the movement of passengers and freight, and this role is becoming more important day by day so that air transportation accounts for a significant share of the transportation problem. There is a growing demand for air travel so it is not unexpected that the demand for air travel will multiply in the coming years. This has created many problems in recent years such as delays, traffic, and air accidents.

The scheduling problem is one of the most important problems in the world today that has a significant impact on increasing the efficiency of production and transportation systems Zeng et al. [1]. Scheduling refers to the allocation of limited resources to activities that require that resource and is a kind of decision-making activity that is done to optimize one or more goals Ng et al. [2]. As a result, aircraft scheduling is one of the most important problems and factors affecting the transportation, industry and customer satisfaction. This problem is to determine the optimal sequence of landing or take-off and assigning them to different and same runways, taking into account the limitations of parking spaces so that the total cost of flight delays is minimized Lambelho et al. [3]. In other words, the Aircraft Scheduling Problem (ASP) deals with the scheduling of aircraft on parallel runways. Each aircraft has its weight penalty and can operate on a runway when ready Zhang et al. [4]. The actual operation time cannot be before the ready time and after the deadline. This time should be as close as possible to the target time of the aircraft Yang et al. [5]. It is known as the time window from the ready time to the deadline. It is impossible to deviate from the deadline. The aircraft in question is not assigned to the runway and the scheduling is known as infeasible if the aircraft operation time exceeds the deadline Shakibayifar et al. [6]. The target time can be predetermined, but the operation time depends entirely on the landing or take-off conditions. Thus, an aircraft may not be able to land or take-off at or near its target time Çiftçi and Özkır [7]. Priority is given to landing rather than take-off, and priority is also given to large aircraft Zhang et al. [4]. Besides, the required separation time between the aircraft in question and other aircraft must be considered. Separation time is considered to prevent the risk of landing or take-off disturbances Sama et al. [8]. When landing or taking off, each aircraft produces turbulence that causes scheduling disturbances. This turbulence varies depending on the type of operation and the size of the aircraft Sama et al. [8]. Hence, the problems of scheduling in this area fall into two general categories: 1) airline problems including fleet, passenger, crew and flight crew allocation, and aircraft maintenance. 2) Problems related to take-off and landing restrictions on one runway to take-off and landing on different runways on the one hand and restrictions such as aircraft size, number of passengers, emergency landing, maintenance and failure of runways, weather conditions, etc. which take the problem out of its initial state and disrupt the initial schedule. Hence, a rescheduling based on the new conditions is required. Some studies focus on different heuristic algorithms and methods for expressing flight schedules due to the complexity of aircraft landing and take-off. Esmaeilidouki et al. [9] solved a problem of routing and transporting hazardous materials. They used a Genetic Algorithm (GA) to pay attention to the time of transportation and routing of materials.

Simultaneously with other parts of the world, flight scheduling in Iran seems necessary due to the dynamics of distance scheduling due to the increase in flights and, consequently, the expansion of flight-related problems on the one hand and the impossibility of developing airport runways in the short term and the high cost of these projects on the other hand. Moreover, constraints such as accessible runway, adverse weather conditions, emergency landing, fuel shortages, security accidents, the unpredictability of flight during landing in general and for Iranian airports in particular, waste of time for cargo delivery, delays and crowds on departure, and the proximity of Iranian airports to major cities that cause problems for residents near airports such as air pollution, noise pollution, etc. and cause the impossibility of flying at night or incurring additional costs for distance travel, etc. make it necessary to pay attention to flight schedules under conditions of uncertainty.

Finally, in Iranian airports, including Tehran airport, problems such as a wide flight range can be mentioned, which has caused the average flight time to be unreasonably extended. On the other hand, problems such as aircraft idle times can be mentioned. The airport would have achieved better quality for both flight and customer service if there was a proper flight schedule. Thus, the main problem of this study is to develop a model for scheduling the time interval between flights so that more benefits and lower costs are achieved. In this study, an attempt has been made to provide a regular schedule taking into account the dynamic conditions at Tehran airport using scientific methods. In this way, improvements can be expected in various areas such as time interval scheduling, robust scheduling, attention to various components, time and cost savings, and so on.

2 | Literature Review

Airlines play an important role in transportation today, and air transportation has a major share of transportation Salehipour et al. [10]. As demand for air transportation grows rapidly, global air traffic is expected to double over the next 15 years. It is even expected to triple in some places. Many large airports are at high risk of air traffic delays or will be soon Zhou et al. [11]. The first idea to solve this problem is to increase the capacity of airports, however, this has also become a major problem Arkind [12]. In the current airport system, runways are considered the primary bottleneck at the airport Idris et al. [13]. Because the landing and take-off of all aircraft depend on the condition of the runways. So, it can be argued that a slight increase in runway efficiency significantly increases the efficiency of the airport. Many researchers have focused on the runway system, and one of the most important operational problems is the ASP. This problem tries to make the most of the runway by scheduling the aircraft landing and take-off as much as possible in a predetermined interval.

With the passage of the Air Transport Liberalization Act in 1978, the way was paved for fundamental changes in the aviation industry Sinha [14] so that airlines could determine the flight route and ticket price of each route themselves. This created a competitive environment between airlines Sama et al. [15]. Today, according to forecasts, demand for aviation is expected to grow at an annual rate of 3% to 5%, despite the recent recession. Therefore, increased traffic causes high obstruction in the terminal areas and delays in the arrival of aircraft and creates long queues in cargo departure areas Fernandes et al. [16].

In this way, total air traffic is steadily increasing, and the number of commercial aircraft used will double over the next two decades Lieder and Stolletz [17]. Matching more flights is a significant challenge given the current level of transportation at busy airports. Runway capacity is often a limiting factor that creates plans to offer additional flights at the airport. Also, the allocation of the fleet has its costs and rules, which are mentioned below. As such, airlines are forced to use powerful tools to make informed decisions, reduce costs, and increase their share of existing demand to survive and establish themselves in a competitive market. One of these tools is the use of systematic scheduling approaches based on mathematical logic in different sectors of airlines. One of the main factors affecting the use of runways is the implementation of the minimum separation between aircraft landing, which is rooted in safety considerations Lee et al. [18]. Wave vortices are circulating air masses that are produced as a result of the flight. These vortices can be dangerous for one aircraft below another. The vortices generated by larger aircraft are stronger but they will not affect the safe operation of the aircraft if the aircraft is at a reasonable distance from another. Besides, if the lower aircraft is lighter than the upper, these vortices will have a greater impact on the lighter aircraft. Therefore, the minimum required distance between aircraft depends on the weight of the upper and lower aircraft. As a result, effective scheduling will help prevent lighter aircraft from landing immediately after a heavier aircraft lands or takes off at Zhou et al. [11].

Flight scheduling is a major part of an airline's operations because a variety of factors must be considered in developing a schedule, and flight operations must be highly safe and reliable. Developing a flight schedule or sub-schedule usually consists of a reciprocating process. This process is very time-consuming to reach an operational flight schedule and is usually done over six months Fernandes et al. [16]. In addition to the safety issues that are the responsibility of air traffic control, other stakeholders are very interested in how the landing is scheduled. The downside is the concern for airlines and airports. Airport operations, such as missions to patrol and carry passengers' luggage, require careful scheduling, and delays in a landing may have detrimental effects on similar operations for subsequent aircraft. Airlines prefer schedules that minimize fuel costs Zhang et al. [4]. In studies by Allahverdi et al. [19] and Ball et al. [20], different problem-solving approaches and objective functions were reviewed in the literature related to flight schedules. In particular, the main objective functions include minimizing delays and costs. Costs are calculated based on deviations from the nominal schedule in terms of delays. Regarding the arrival schedule, Zhan et al. [21] predicted and assigned the sum of the differences between the landing times of each aircraft. Sama et al. [15] limited aircraft delays and deviations from the timetable by considering aviation priorities (aviation priorities refer to the classification of aircraft for a flight on the runway. For example, international aircraft are given priority due to the importance of on-time flights, and domestic flights are next). Khaksar and Sheikholeslami [22] presented a method for airline delay prediction via machine learning algorithms based on data mining, random forest Bayesian classification, K-means clustering, and hybrid approach and calculated delay occurrence and magnitude in both Iran and USA networks. In a study by Beasley et al. [23], the problem of aircraft displacement was investigated by considering transportation costs using the distance-to-cost adjustment approach. In particular, additional penalties should be considered if the aircraft is delayed concerning the initial solution. Bennel et al. [24] allocated landing times for aircraft based on the evaluation of a specific route by minimizing flight time and using routing patterns by maximizing the minimum time between two landings. Hu and Di Paolo [25] considered two objective functions: minimizing the delay of all aircraft and maximizing the length of all arrival queues. The first objective function emphasizes the operating cost of the aircraft, but the second objective function emphasizes the objective functions, which focus on the efficiency of using the airport capacity. Bennell et al. [26] examined the dynamic landing schedule at a single-runway airport. They considered the time window limit for each landing time and the minimum separation distance between successive landings where the separation time depends on the weight classes of the two aircraft at landing. The multi-objective formula was proposed.

According to runway capacity, delays and fuel costs due to aircraft maneuvering, and additional flight time to reach the landing schedule. Kenan et al. [27] investigated the landing and take-off schedules of aircraft in terms of runway interdependencies and their heterogeneity and proposed an optimization method for the flight scheduling problem with general runway configurations (it is the runway that is used by 80% of flights, and there are some dedicated runways for private or military aircraft or giant aircraft). Cheng et al. [28] introduced the concept of flight operation risk assessment system for an airline and discussed the correlation between a risk factor and its sub components with fuzzy inference system. They also developed algorithms to identify the critical risk factors based on sensitivity of the risk factor and heuristic search.

Kim et al. [29] developed a mathematical model to provide a basis for planning airport facilities and increasing existing services in Incheon International Airport. It was found that the proposed model has good prediction capability for traffic volume on the Incheon International Airport Expressway on an hourly basis.

Tavakkoli Moghaddam et al. [30] considered the issue of aircraft meeting scheduling as a single band and solved it using a fuzzy planning approach. In their work, they proposed methods for the problem of aircraft landing with the shortest waiting time in the desired time window in critical situations, such as the closest landing time to the target time for each aircraft or the minimum landing time of aircraft.

Rashidi Komijan et al. [31] present a mathematical model for an integrated airline fleet assignment and crew scheduling. They use Vibration Damping Optimization (VDO) algorithm to an appropriate solution to their problem during a reasonable time period. An experimental design based on the Taguchi method was taken into account too. In the discussion of solution methods. Hassanpour et al. [32] present a robust bi-level programming model for designing a closed-loop supply chain and use a robust bi-level and GA for solve the problem.

The landing and take-off of each aircraft must be assigned to a runway or time. However, the requirements for separating two aircraft are met depending on the aircraft tail and minimizing the cost of delays. Some runways can only be used for landing, take-off, or certain types of aircraft. At the same

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time, additional separation restrictions should be considered in scheduling airport runways. The dynamic scheduling approach presented in this study solves realistic examples of the problem for optimization in short computation time. Moreover, this study proposes a scheduling horizon for large examples that give near-optimal results. Therefore, in a comprehensive flight schedule, the modeling process is complex and difficult due to the large size of the problem, the types of constraints, the types of objective functions to be optimized, the parameters, and the types of decision variables. This is why researchers divide the problem into several smaller, independent problems and then solve each one separately.

The main problems proposed in the flight schedule are as follows:

I. Aircraft landing and take-off schedule design.
II. Fleet al.location to flight.
III. Determining the flight path and aircraft maintenance schedule (allocation of aircraft to flight).
IV. Flight crew scheduling.

However, each of the more detailed problems needs to be optimized in each of the sub-problems. The flight scheduling problem, which covers all sub-problems, will not necessarily be optimal if the optimal solution for each sub-problem is discrete. In addition to the problem, in such a case, there is still a reciprocating process between each of the sub-problems, especially with the first stage, the landing and take-off schedule, so that the flight schedule is in a relatively optimal state, which will waste a lot of time. Therefore, adopting a different approach that considers all sub-problems as discrete can provide a more optimal solution to the flight scheduling problem and significantly reduce the time interval of the scheduling process. So, it seems necessary to adopt such an approach.

In this study, a robust mathematical model is designed and solved for the problem of optimal scheduling of passenger aircraft flight time interval at Tehran airport.

3 | Mathematical Modeling

The ASP is to determine the optimal sequence of landing or take-off and assigning them to different and same runways, taking into account the limitations of parking spaces so that the total cost of flight delays is minimized. In other words, the ASP deals with the scheduling of aircraft on parallel runways. Hence, the modeling assumptions are as follows:

I. The departure time of each aircraft depends on their sequence on the runway.
II. Each runway can direct a maximum of one aircraft at any moment.
III. Each aircraft can take-off or land on a maximum of one runway at any moment.
IV. Runways are not continuously available.
V. All flight times are as robust uncertainty.

Indices

- *i: runway*
- *j: aircraft (j)*
- *l: aircraft (l)*
- *t: time interval*

Input parameters

n: the number of flights.

m^t: the number of ready runways in each period t.

d_j: The flight time of aircraft j.

P_{il}: The flight duration of aircraft l on the runway i.

r_j: Access time for aircraft j to start the take-off process.

α_j: Cost of haste in the landing/take-off of aircraft j.

β_j: Cost of delays in landing/take-off of aircraft j.

M_{ij}^tt: If it were possible for aircraft j to fly or land on runway i in period t, 1, and, otherwise, 0.

S_{jl}^t: The ready time for aircraft l when ready to fly/land on one of the runways after aircraft j in step t.

ch_{il}^t: The ready time for aircraft l when the first aircraft to take off or land on runway i in stage t.

av_i^t: The time to access runway i in period t.

pd_j^t : The probability of runway disturbances after landing/take-off of aircraft j in period t.

R^t: The time required to repair the runway in each period t.

M': A large positive integer number.

Decision variables

X_{ij}^t: If aircraft j flies/lands on runway i in period t, 1, and, otherwise, 0.

Y_{ijl}^t: If aircraft j flies/lands on runway i in period t before aircraft l, 1, and, otherwise, 0.

C_j^t: The time to complete the flight of aircraft j in period t.

C_l^t: The time to complete the flight of aircraft l in period t.

E_j: The haste time of aircraft j for landing/take-off.

T_j: The delay time of aircraft j for landing/take-off.

The model variables including E, C, and T have non-negative integers, and variables X and Y have values of zero and one.

3.1 | Decision Variables

$$\text{Min } C = \sum_{j=1}^{n} \alpha_j E_j + \beta_j T_j.$$

The objective function of the model is equal to the sum of the acceleration and delay times of the flights. In this formula, the values of the decision variables Ej and Tj for j-type aircraft are obtained from *Eqs. (1)* and *(2)*, respectively.

$$E_j = \max\left(0, d_j - C_j^t\right), \quad (1)$$

$$T_j = \max\left(0, C_j^t - d_j\right), \quad (2)$$

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$$\sum_{l=1}^{m^t} X_{ij}^t = 1 \quad \text{for all } t, j, \tag{3}$$

$$\sum_{l=1}^{n} Y_{ijl}^t \leq X_{ij}^t \quad \text{for all } i, j, t \quad j \neq 1, \tag{4}$$

$$\sum_{j=0}^{n} Y_{ijl}^t = X_{il}^t \quad \text{for all } t, i, l \quad l \neq j, \tag{5}$$

$$\sum_{l=1}^{n} Y_{i0l}^t = 1 \quad \text{for all } t, i, \tag{6}$$

$$X_{ij}^t \leq M_{ij}^t \quad \text{for all } t, i, j, \tag{7}$$

$$C_l^t - C_j^t \geq S_{jl}^t + P_{il} * Y_{ijl}^t + pd_j^t * R^t + \left(Y_{ijl}^t - 1\right) * M \quad \text{for all } t, i, j, l, \tag{8}$$

$$C_j^t \geq 0 \quad \text{for all } t, j, \tag{9}$$

$$C_l^t - C_l^{t-1} \geq \sum_{i=1}^{m^t} \sum_{j=1}^{n} Y_{ijl}^t * S_{jl}^t + \sum_{i=1}^{m^t} ch_{il}^t * Y_{i0l}^t + \sum_{i=1}^{m^t} \sum_{j=1}^{n} P_{il} * Y_{ijl}^t + \sum_{i=1}^{m^t} P_{il} * Y_{i0l}^t + \sum_{i=1}^{m^t} \sum_{j=1}^{n} pd_j^t * R^t * Y_{ijl}^t \quad \text{for all } t, l \quad j \neq l, \tag{10}$$

$$C_l^t \geq \sum_{i=1}^{m^t} av_i^t * Y_{i0l}^t + \sum_{i=1}^{m^t} ch_{il}^t * Y_{i0l}^t + \sum_{i=1}^{m^t} P_{il} * Y_{i0l}^t \quad \text{for all } t, l, \tag{11}$$

$$C_j^0 \geq r_j \quad \text{for all } j, \tag{12}$$

$$T_j \geq C_j^t - d_j \quad \text{for all } t, j, \tag{13}$$

$$T_j \geq 0 \quad \text{for all } j, \tag{14}$$

$$E_j \geq d_j - C_j^t \quad \text{for all } t, j, \tag{15}$$

$$E_j \geq 0 \quad \text{for all } j. \tag{16}$$

3.2 | The Limitations of the Proposed Model

Constraint (3) indicates that each aircraft can land/take off on one and only one runway in each period t. *Constraints (4)* and *(5)* ensure that each aircraft has a landing/take-off operation immediately before and after only one other aircraft on the runway in each period t. *Constraint (6)* specifies the first flight on runway i in each period t. *Constraint (7)* introduces limited access to the runway. As stated in the model input parameters section, if aircraft j can fly/land on runway i in period t, the value of parameter M_{ij}^t will be 1. Otherwise, it will be 0. The possibility of flight/landing of aircraft j on runway i in period t is determined according to the movement set of aircraft j, i.e. M_j^t, which is a subset of runways M^t and includes all runways on which aircraft j can land/take off. This constraint, thus, constrains the model to consider M_{ij}^t, which is one of the input parameters of the model, for assigning runway i to aircraft j and, consequently, assigning the value of 1 to the decision variable X_{ij}^t. This assignment is made if the value of M_{ij}^t is 1 such as X_{ij}^t. *Constraint (8)* ensures that the landing/take-off time of the aircraft is the result of the time it takes for the aircraft to be ready for flight, the duration of flight on the runway, and the likelihood of flight disturbances. *Constraint (9)* ensures that the flight time starts from zero. *Constraint (10)* ensures that the flight schedules do not interfere with each other. *Constraint (11)* ensures that the first aircraft does not have a problem flying. *Constraint (12)* specify the completion time of each flight. *Constraints (13)* and *(14)* specify the constraints on delay times for flight j. *Constraints (15)* and *(16)* specify the constraints on haste times for flight j.

3.3 | Bertsimas and Sim Robust Uncertainty Approach

The robust optimization specifies a suitable uncertainty set for imprecise input data and gives a solution that ensures feasibility in all amounts of uncertain parameters within the uncertainty set Ben-Tal and Nemirovski [33].

According to the evaluation, uncertainty in the flight time is added to the model using robust scheduling and the Bertsimas and Sim approach. With this change, *Constraint (8)* is modified as the Bertsimas model. Therefore, the proposed model is linear. Studies show that flight time is one of the important parameters whose values may exceed the nominal values. As a result, considering this parameter in uncertainty conditions can bring the proposed model closer to the reality of the problem. Robust scheduling and the Bertsimas and Sim approach are used to consider uncertainty in the flight time. Robust optimization seeks

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optimal or near-optimal solutions that are likely to be feasible. The Bertsimas and Sim approach is one of the four main approaches for considering uncertainty in robust scheduling. This section briefly mentions this approach. For this purpose, the following linear programming model is considered.

$$\begin{aligned} &\text{Min } \textstyle\sum_j c_j x_j, \\ &\text{s.t.} \\ &Ax \leq b. \end{aligned} \tag{17}$$

In this model, it is assumed that only the right-hand coefficients in the constraints, matrix A, have uncertain values, and the values of this matrix, i.e. a_{ij}, fluctuate in the range $[\tilde{a}_{ij} - \hat{a}_{ij}, \tilde{a}_{ij} + \hat{a}_{ij}]$, where $\tilde{a}_{ij}$ and $\hat{a}_{ij}$ are the nominal values and the maximum deviation of parameter a_{ij}, respectively. The proposed Bertsimas and Sim robust model is as follows:

$$\begin{aligned} &\min \sum_j c_j x_j, \\ &\text{s.t.} \\ &\textstyle\sum_j \tilde{a}_{ij} x_j + z_i \Gamma_i + \sum_{j \in J_i} \mu_{ij} \leq b_i \quad \text{for all } i, \\ &z_i + \mu_{ij} \geq \hat{a}_{ij} x_{ij} \quad \text{for all } i, j, \\ &z_i, \mu_{i,j} \geq 0 \quad \text{for all } i, j, \end{aligned} \tag{18}$$

where z_i and μ_{ij} are dual auxiliary variables, and parameter Γ_i, called the uncertainty budget, indicates the level of conservatism that is chosen according to the importance of the constraint as well as the risk-taking of the decision-maker. Hence, *Constraints (8)*, *(10)* and *(11)* become *Constraints (19)* to *(22)* according to the Bertsimas and Sim robust model.

$\hat{p}_{il}$: The tolerance of flight time of aircraft l on runway i.

Γ_{il}: The uncertainty budget for flight time.

Variables

pp_{il} and q_{ilt}: The robust model variables.

$$C_l^t - C_j^t \geq S_{jl}^t + P_{il} * Y_{ijl}^t + \Gamma_{il} pp_{il} + q_{ilt} + pd_j^t * R^t + \left(Y_{ijl}^t - 1\right) * M \quad \text{for all } t, i, j, l, \tag{19}$$

$$C_l^t - C_l^{t-1} \geq \sum_{i=1}^{m^t} \sum_{j=1}^{n} Y_{ijl}^t * S_{jl}^t + \sum_{i=1}^{m^t} ch_{il}^t * Y_{i0l}^t + \sum_{i=1}^{m^t} \sum_{j=1}^{n} P_{il} * Y_{ijl}^t + \sum_{i=1}^{m^t} P_{il} * Y_{i0l}^t + \Gamma_{il} pp_{il} + q_{ilt} + \sum_{i=1}^{m^t} \sum_{j=1}^{n} pd_j^t * R^t * Y_{ijl}^t \quad \text{for all } t, l \quad j \neq l, \tag{20}$$

$$C_l^t \geq \sum_{i=1}^{m^t} av_i^t * Y_{i0l}^t + \sum_{i=1}^{m^t} ch_{il}^t * Y_{i0l}^t + \sum_{i=1}^{m^t} P_{il} * Y_{i0l}^t + \sum_{i=1}^{m^t} P_{il} * Y_{i0l}^t + \Gamma_{il} pp_{il} + q_{ilt} \quad \text{for all } t, l, \tag{21}$$

$$pp_{il} + q_{ilt} \geq \hat{p}_{il} * Y_{i0l}^t \quad \text{for all } i, l, t. \tag{22}$$

4 | Funding

In this section, the proposed mathematical model is validated. The collected data indicate that the movement position of the aircraft does not follow the same distribution functions. The status of the mathematical model parameters is as follows based on the timing performed.

4.1 | Aircraft Ready Time

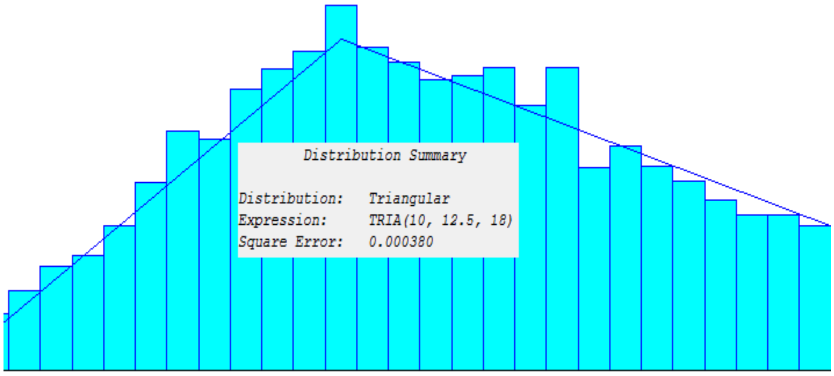

Fig. 1. Aircraft ready time on the runway.

The ready time parameter of aircraft j when selected as the first aircraft.

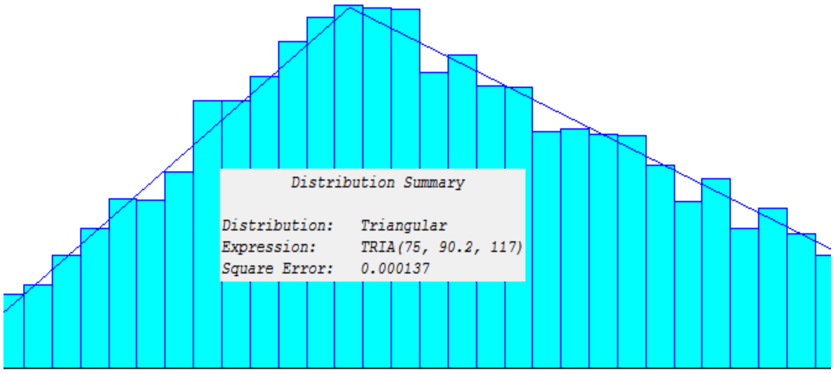

Fig. 2. Aircraft's ready time when selected as the first aircraft.

According to the evaluation, the aircraft's ready time for landing and flight follows the triangular function with a minimum value of 10 minutes and a maximum value of 18 minutes, which is coded based on the obtained values of the mathematical model.

The ready time parameter of aircraft j when selected as the first aircraft.

Table 1. Adjustment of the mathematical model parameters.

The Mathematical Model Parameters	Intended Values
The flight time of aircraft j	U~ [10,30]
The flight time of aircraft j on the runway	U~ [1,3]
The time to access aircraft j to start the take-off process	U~ [1,6]
The cost of hastening the landing/take-off	U~ [20,50] $
The cost of Delays in landing/take-off	U~ [80,100] $
The possibility of runway disturbances after landing/takeoff	0.35

According to the adjustment of the mathematical model parameters, the flight schedule of one of the airports is considered as follows (it is worth mentioning that small, medium, and large runways are selected for the schedule. Therefore, 20 aircraft are investigated in 3 runways over a 24-hour schedule. The flight schedule is as follows:

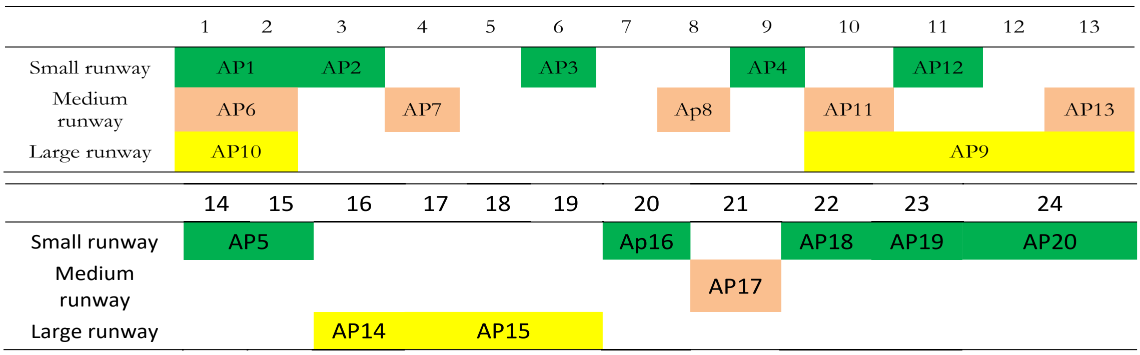

Fig. 3. The flight schedule for 24 hours.

The evaluation of the designed problem and flight time of the aircraft show that 50% of the aircraft fly on small runways, 30% on medium runways, and 20% on large runways. The flight schedule for 24 hours is shown in *Fig 3*. Since the problem under study is NP-HARD, in this section, the mathematical model is evaluated using genetic meta-heuristic and imperialist competitive algorithms.

4.2 | Adjusting the Meta-Heuristic Algorithm Parameters

One of the most important steps in designing meta-heuristic algorithms to achieve optimal solutions is algorithm calibration. Different values of control parameters of these algorithms may affect computation indices including solution quality and computation time, so a series of calibration tests are often performed to find the optimal combination of different values of algorithm control parameters. The algorithms proposed in this study are genetic and imperialist competitive algorithms. GA control parameters include initial population size (Pop_{GA}), crossover rate (P_c), mutation rate (P_m), and the maximum number of generations (G_{max}). The imperialist competitive algorithm control parameters are the number of neighborhoods produced (Pop_{ICA}), the number of iterations (Decade), and the percentage effect of the total power of each imperial colony on its power (PICA). Each of these parameters affects the computation indices in a certain range of their values and has a negligible effect outside this range. The computation indices used in the tests of this section and future sections are the mean values of the objective function for the optimal solutions and their mean computation times per ten iterations of the algorithm. A set of tests based on the Taguchi method is designed to investigate the interaction of control parameters of the proposed algorithms and achieve their optimal combination. Each of the parameters for each of the proposed algorithms in the previous section is tested at three levels. Solution levels are the mean solutions obtained and the mean computation times. To simultaneously consider the quality of solutions and computation times, the values of the two are normalized and added together. First the parameters of the GA and then the parameters of the Imperialistic Competitive Algorithm (ICA) algorithm were examined. *Table 2* shows the desired factors and their levels for the GA. The tests required to examine the various combinations of factors and the corresponding solutions can be seen in *Table 3*. The generated data are analyzed by MINITAB 14 software, and the results are provided in the following tables.

Table 2. Factors and their levels.

Factor	Levels
Pop_{GA}	200, 300, 400
P_c	0.8, 0.7, 0.6
P_m	0.15, 0.12, 0.10
G_{max}	200, 300, 400
P_{mu}	0.10, 0.15, 0.2

To simultaneously examine the effect of factors on the quality of solutions and computation times, their values are normalized, added together, and become a solution variable. Finally, the inverse of this value is calculated and considered as the solution variable. The larger the value, the better. This can be seen in *Table 4*.

Table 3. Combinations of factors and corresponding solution levels in multifactorial tests.

Pop_{GA}	P_c	P_m	P_{mu}	G_{max}	Solution	CPU(s)
200	0.6	0.10	0.10	200	164.00	6.56
200	0.6	0.10	0.10	300	42.00	11.80
200	0.6	0.10	0.10	400	46.70	13.73
200	0.7	0.12	0.15	200	40.00	8.50
200	0.7	0.12	0.15	300	13.67	12.60
200	0.7	0.12	0.15	400	32.33	13.75
200	0.8	0.15	0.20	200	66.33	12.45
200	0.8	0.15	0.20	300	26.33	16.58
200	0.8	0.15	0.20	400	27.00	20.70
300	0.6	0.12	0.20	200	20.67	14.17
300	0.6	0.12	0.20	300	14.33	23.07
300	0.6	0.12	0.20	400	48.33	12.80
300	0.7	0.15	0.10	200	20.33	16.21
300	0.7	0.15	0.10	300	21.67	22.89
300	0.7	0.15	0.10	400	44.67	13.21
300	0.8	0.10	0.15	200	18.67	22.58
300	0.8	0.10	0.15	300	22.33	23.54
300	0.8	0.10	0.15	400	49.10	12.51
400	0.6	0.15	0.15	200	15.00	28.12
400	0.6	0.15	0.15	300	45.20	14.30
400	0.6	0.15	0.15	400	26.57	20.01
400	0.7	0.10	0.20	200	14.87	27.95
400	0.7	0.10	0.20	300	14.65	27.80
400	0.7	0.10	0.20	400	13.00	29.14
400	0.8	0.12	0.10	200	8.60	34.00
400	0.8	0.12	0.10	300	9.20	31.23
400	0.8	0.12	0.10	400	7.60	31.46

Table 4. Combinations of factors and normalized solution levels in multifactorial tests.

Pop_{GA}	P_c	P_m	P_{mu}	G_{max}	Normalized	1/Normalized
200	0.6	0.10	0.10	200	0.200401	4.99
200	0.6	0.10	0.10	300	0.070722	14.14
200	0.6	0.10	0.10	400	0.079804	12.53
200	0.7	0.12	0.15	200	0.062105	16.10
200	0.7	0.12	0.15	300	0.039810	25.12
200	0.7	0.12	0.15	400	0.063385	15.78
200	0.8	0.15	0.20	200	0.099832	10.02
200	0.8	0.15	0.20	300	0.061938	16.15
200	0.8	0.15	0.20	400	0.070604	14.16
300	0.6	0.12	0.20	200	0.050836	19.67
300	0.6	0.12	0.20	300	0.060636	16.49
300	0.6	0.12	0.20	400	0.079888	12.52
300	0.7	0.15	0.10	200	0.054357	18.40
300	0.7	0.15	0.10	300	0.068697	14.56
300	0.7	0.15	0.10	400	0.076483	13.07
300	0.8	0.10	0.15	200	0.064667	15.46
300	0.8	0.10	0.15	300	0.070699	14.14
300	0.8	0.10	0.15	400	0.080214	12.47
400	0.6	0.15	0.15	200	0.071084	14.07
400	0.6	0.15	0.15	300	0.079179	12.63
400	0.6	0.15	0.15	400	0.068788	14.54
400	0.7	0.10	0.20	200	0.070609	14.16
400	0.7	0.10	0.20	300	0.070070	14.27
400	0.7	0.10	0.20	400	0.070749	14.13
400	0.8	0.12	0.10	200	0.075026	13.33
400	0.8	0.12	0.10	300	0.070403	14.20
400	0.8	0.12	0.10	400	0.069012	14.49

Table 5. Estimated correlation coefficients of the model for SN ratios.

Term	Coef	SE Coef	T	P
Constant	22.9674	0.4156	55.270	0.000
Pop_{GA}200	-0.4973	0.5877	-0.846	0.410
Pop_{GA}300	0.5624	0.5877	0.957	0.353
P_c 0.6	-0.8177	0.5877	-1.391	0.043
P_c 0.7	1.0433	0.5877	1.775	0.025
P_m 0.10	-1.1060	0.5877	-1.882	0.038
P_m0.12	1.1476	0.5877	1.953	0.0۲9
P_{mu} 0.12	-0.9031	0.5877	-1.537	0.144
P_{mu} 0.15	0.7053	0.5877	1.200	0.248
G_{max}200	-0.5723	0.5877	-0.974	0.345
G_{max}300	0.8050	0.5877	1.370	0.009

Factor correlation coefficients for SN ratios are presented in *Table 5*. Coefficients with larger absolute values are more important than other factors. These coefficients are used to rank the factors in the solution table. As can be seen in the table, the factors P_c = 0.6, P_m = 0.10, P_{mu} = 0.12, and G_{max} = 300 have a significant effect on the solutions at the 95% confidence level.

Table 6. Analysis of variance for SN ratios.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pop_{size}	2	5.110	5.110	2.555	0.55	0.589
P_c	2	16.272	16.272	8.136	1.75	0.016
P_m	2	22.877	22.877	11.439	2.45	0.018
P_{mu}	2	12.170	12.170	6.085	1.31	0.299
G_{max}	2	9.267	9.267	4.633	0.99	0.029
Residual Error	14	74.599	74.599	4.662		
Total	24	140.296				

Similar results are presented in *Table 7*, which shows the factor correlation coefficients for the mean solutions. Moreover, the analysis of variance for the SN coefficient and the mean solutions are performed for the tested factors, and the results are given in *Tables 6* and *8*. According to the analysis of variance, the factors P_m , P_c and $G_{max}$with a p-value of less than 0.05 have a significant effect on the solutions as expected.

Table 7. Estimated correlation coefficients of the model for mean solutions.

Term	Coef	SE Coef	T	P
Constant	14.5035	0.3741	38.765	0.000
Pop_{GA}200	-0.1711	0.8344	-0.205	0.840
Pop_{GA}300	0.6944	0.8344	0.832	0.417
P_c 0.6	-0.9944	0.8344	-1.192	0.251
P_c 0.7	1.6733	0.8344	2.006	0.042
P_m 0.10	-1.5822	0.8344	-1.896	0.016
P_m0.12	1.9078	0.8344	2.287	0.036
P_{mu} 0,1	-1.2022	0.8344	-1.441	0.169
P_{mu}0.15	1.0867	0.8344	1.302	0.211
G_{max} 200	-0.4811	0.8344	-0.577	0.042
G_{max}300	1.2411	0.8344	1.487	0.000

Table 8. Analysis of variance for mean solutions.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pop_{GA}	2	7.069	7.069	3.534	0.38	0.692
P_c	2	38.249	38.	19.124	2.03	0.022
P_m	2	56.241	56.241	28.121	2.99	0.006
P_{mu}	2	23.756	23.756	11.878	1.26	0.309
G_{max}	2	21.145	21.145	10.572	1.12	0.001
Residual Error	14	150.370	150.370	9.398		
Total	24	296.829				

Table 9. SN ratio solution.

Level	Pop_{size}	P_c	P_m	P_{mu}	G_{max}
1	22.47	22.15	21.86	22.06	22.40
2	23.53	24.01	24.12	23.67	23.77
3	22.90	22.74	22.93	23.17	22.73
Delta	1.06	1.86	2.25	1.61	1.38
Rank	5	2	1	3	4

Solution levels are evaluated according to mean solution indices and SN ratios, and factors are ranked to determine the priority or degree of importance of each factor. The mean solution index for each level of each factor can be seen in the solutions table. The ranking of the factors according to the solution analysis concerning SN coefficients and means can be seen in *Tables 9* and *10*. Accordingly, the P_m factor has the highest rank in both tables, and the P_c factor has the second rank. The ranking of other factors is the same for the mean solution indices and SN coefficients.

Table 10. Mean solutions.

Level	Pop_{size}	P_c	P_m	P_{mu}	G_{max}
1	14.33	13.51	12.92	13.30	14.02
2	15.20	16.18	16.41	15.59	15.74
3	13.98	13.82	14.18	14.62	13.74
Delta	1.22	2.67	3.49	2.29	2.00
Rank	5	2	1	3	4

Factor interaction analysis is used to fine-tune the levels of factors. These effects can be seen in the following figures (*Figs. 4* and *5*).

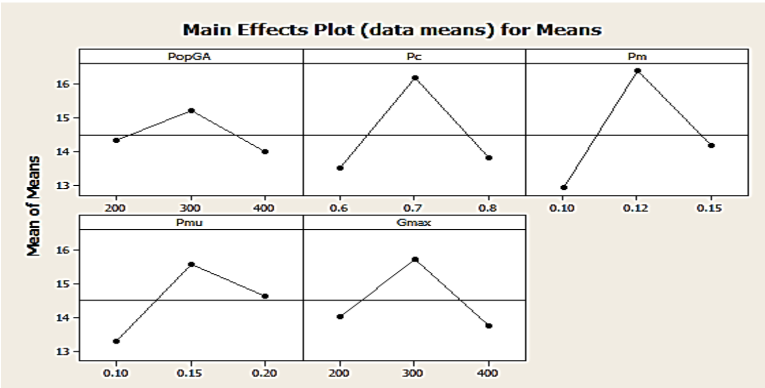

Fig. 4. Mean solutions.

As shown in *Fig. 4*, the mean solution index is maximized by Pop_{GA} factor at level 300, by P_c factor at level 0.6, by $P_m$factor at level 0.12, by P_{mu} factor at level 0.15, and by G_{max}factor at level 300. Examining the levels of the factors in *Fig. 5* shows that the factors maximize the SN index at similar levels.

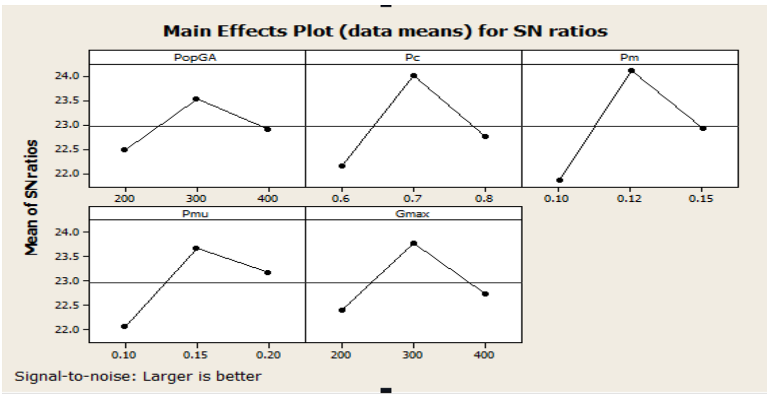

Fig. 5. Mean SN ratio.

Thus, the values of the control parameters of the proposed GA are adjusted according to the following table.

Table 11. Optimal values of control parameters.

Factor	Levels
Pop_{GA}	300
P_c	0.7
P_m	0.12
P_{mu}	0.15
G_{max}	300

Table 12 shows the factors and their levels for the imperialist competitive algorithm. The tests required to examine the various combinations of factors and the corresponding solutions are presented in *Table 13*.

Table 12. Factors and their levels.

Factor	Levels
Pop_{GA}	300, 400, 500
decade	200, 300, 400
P_{ICA}	0.08, 0.10, 0.12

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Table 13. Combinations of factors and solution levels in multifactorial tests.

Pop_{ICA}	Decade	P_{ICA}	Solution	CPU (s)
300	200	0.08	85.2	0.66
300	200	0.08	40.6	0.82
300	200	0.08	40.2	1.13
300	300	0.10	36.0	0.65
300	300	0.10	23.0	0.83
300	300	0.10	27.8	1.14
300	400	0.12	46.2	0.65
300	400	0.12	31.4	0.80
300	400	0.12	30.8	1.15
400	200	0.10	19.0	1.29
400	200	0.10	19.0	1.86
400	200	0.10	25.6	0.98
400	300	0.12	30.6	1.27
400	300	0.12	37.8	1.87
400	300	0.12	36.2	0.99
400	400	0.08	19.0	1.28
400	400	0.08	21.8	1.92
400	400	0.08	23.0	0.98
500	200	0.12	21.4	2.55
500	200	0.12	24.6	1.25
500	200	0.12	19.0	1.77
500	300	0.08	22.6	2.59
500	300	0.08	26.0	1.24
500	300	0.08	23.4	1.66
500	400	0.10	32.2	2.60
500	400	0.10	28.2	1.30
500	400	0.10	22.6	1.74

To simultaneously examine the effect of factors on the quality of solutions and computation times, their values are normalized, added together, and become a solution variable. Finally, the inverse of this value is calculated and considered as the solution variable. The larger the value, the better. This can be seen in *Table 14*.

Table 14. Combinations of factors and normalized solution levels in multifactorial tests.

Pop_{ICA}	Decade	P_{ICA}	Normalized	1/Normalized
300	200	0.08	0.122624	8.16
300	200	0.08	0.072106	13.87
300	200	0.08	0.080000	12.50
300	300	0.10	0.061851	16.17
300	300	0.10	0.050734	19.71
300	300	0.10	0.065022	15.38
300	400	0.12	0.074394	13.44
300	400	0.12	0.060252	16.60
300	400	0.12	0.068981	14.50
400	200	0.10	0.058258	17.17
400	200	0.10	0.073676	13.57
400	200	0.10	0.057989	17.24
400	300	0.12	0.071981	13.89
400	300	0.12	0.097065	10.30
400	300	0.12	0.071294	14.03
400	400	0.08	0.057987	17.25
400	400	0.08	0.078742	12.70
400	400	0.08	0.054791	18.25
500	200	0.12	0.095291	10.49
500	200	0.12	0.064062	15.61
500	200	0.12	0.071241	14.04
500	300	0.08	0.097848	10.22
500	300	0.08	0.065513	15.26
500	300	0.08	0.073676	13.57
500	400	0.10	0.109924	9.10
500	400	0.10	0.069841	14.32
500	400	0.10	0.074857	13.36

Table 15. Estimated correlation coefficients of the model for SN ratios.

Term	Coef	SE Coef	T	P
Constant	22.5770	0.7015	32.184	0.000
Pop_{ICA}300	0.2102	0.9921	0.212	0.852
Pop_{ICA}400	0.5968	0.9921	0.602	0.009
decade200	-0.3813	0.9921	-0.384	0.738
decade300	0.1738	0.9921	0.175	0.045
P_{ICA}0.08	-0.5050	0.9921	-0.509	0.661
P_{ICA}0.10	0.6425	0.9921	0.648	0.037

Table 16. Analysis of variance for SN ratios.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pop_{ICA}	2	13.1550	13.1550	11.5775	4.79	0.026
Pop_{ICA}	2	10.6559	10.6559	10.3279	4.22	0.031
P_{ICA}	2	22.0603	22.0603	19.323	8.49	0.04

Factor correlation coefficients for SN ratios are presented in *Table 15*. Coefficients with larger absolute values are more important than other factors. These coefficients are used to rank the factors in the solution table. As can be seen in the table, the factors Pop_{ICA} = 400, *decade* = 300, and P_{ICA} = 0.1 have a significant effect on the solutions at the 95% confidence level.

Similar results are presented in *Table 17*, which shows the factor correlation coefficients for the mean solutions. Besides, the analysis of variance for the SN coefficient and the mean solutions are performed for the tested factors, and the results are given in *Tables 16* and *18*. According to the analysis of variance, the factors, P_{ICA}, *decade,* and Pop_{ICA} with a p-value of less than 0.05 have a significant effect on the solutions as expected.

Table 17. Estimated correlation coefficients of the model for mean solutions.

Term	Coef	SE Coef	T	P
Constant	14.0996	0.2973	47.433	0.000
$Pop_{ICA}300$	0.3801	0.4204	0.904	0.381
$Pop_{ICA}400$	1.0132	0.4204	2.410	0.030
decade200	-0.4721	0.4204	-1.123	0.280
decade300	-1.9308	0.4204	-4.593	0.000
$p_{ICA}0.08$	-0.5689	0.4204	-1.353	0.197
$P_{ICA}0.10$	1.4109	0.4204	3.356	0.005

Table 18. Analysis of variance for mean solutions.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pop_{ICA}	2	20.817	20.817	10.408	4.36	0.034
decade	2	57.503	57.503	28.751	12.05	0.001
P_{ICA}	2	53.902	53.902	26.951	11.30	0.001
Residual Error	14	33.400	33.400	2.386		
Total	20	165.622				

Table 19. SN ratio solution.

Level	Pop_{ICA}	Decade	P_{ICA}
1	22.79	22.20	22.07
2	23.17	22.75	23.17
3	21.77	22.78	21.77
Delta	1.40	0.59	1.15
Rank	1	3	2

Table 20. Mean solutions.

Level	Pop_{ICA}	Decade	P_{ICA}
1	14.48	13.63	13.53
2	14.93	14.28	15.11
3	12.89	14.39	13.66
Delta	2.05	0.76	1.58
Rank	1	3	2

Solution levels are evaluated according to mean solution indices and SN ratios, and factors are ranked to determine the priority or degree of importance of each factor. The mean solution index for each level of each factor can be seen in the solutions table. The ranking of the factors according to the solution analysis concerning SN coefficients and means can be seen in *Tables 19* and *20*. Accordingly, the Pop_{ICA} factor has the highest rank in both tables, and the P_{ICA} factor has the second rank. The ranking of decade factors is the same for the mean solution indices and SN coefficients. Factor interaction analysis is used to fine-tune the levels of factors. These effects can be seen in the following figures (*Figs. 6* and *7*).

As shown in *Fig. 6*, the mean solution index is maximized by Pop_{ICA}factor at level 400, by decade factor at level 200, and by P_{ICA} factor at level 0.1. Examining the levels of the factors in *Fig. 7* shows that the factors maximize the SN index at similar levels.

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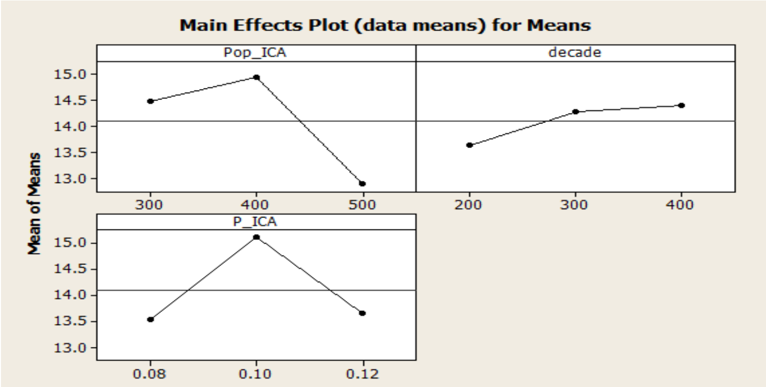

Fig. 6. Mean solutions.

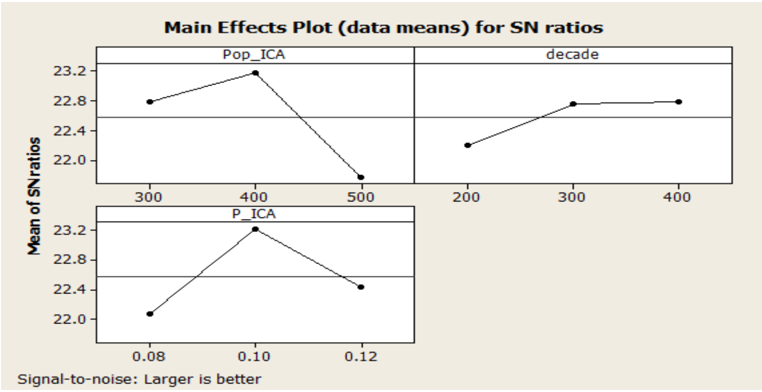

Fig. 7. Mean SN ratio.

Thus, the values of the control parameters of the proposed imperialist competitive algorithm are adjusted according to the following table.

Table 21. Optimal values of control parameters.

Factor	Levels
Pop_{ICA}	400
decade	300
P_{ICA}	0.1

4.3 | Evaluation of Algorithms

A Relative Percent Deviation (RPD) is used as a measure for comparing GA and ICA algorithms *Eq. (23)*. Small, medium and large problems are used to measure the performance of these algorithms. The test results, the best solution, the worst solution, the mean solutions, and the mean execution time are presented in *Table 22*. Moreover, *Table 23* shows the RPD values and the mean execution time. The condition for stopping the algorithms is considered to be 100 seconds. Preliminary tests show that these algorithms usually reach the best solution before this time, and the first time they reach the best value of the objective function is recorded.

$$RPD = \frac{sol_{avg} - sol_{min}}{sol_{min}}. \tag{23}$$

Table 22. Values obtained from different executions for GAMs and both proposed algorithms.

AP	Runway	GAMS Global Optimal	Time	GA Best	Worst	Mean	Time	ICA Best	Worst	Mean	Time
	3	1	0:00:06	1	1	1	0:00:16	1	1	1	0:00:14
4	5	4	0:00:09	4	4	4	0:00:17	4	4	4	0:00:17
	7	9	0:00:11	9	9	9	0:00:20	9	9	9	0:00:19
	3	6	0:00:10	6	6	6	0:00:30	6	6	6	0:00:30
6	5	12	0:05:42	12	12	12	0:00:37	11	12	11.33	0:00:33
	7	11	0:19:11	11	11	11	0:00:43	11	11	11	0:00:43
	3	15	0:56:01	15	15	15	0:01:21	15	15	15	0:01:47
10	5	-	-	20	26	21.2	0:02:33	21	26	22.2	0:02:29
	7	-	-	18	22	19.4	0:03:00	14	17	15.6	0:03:21
	3	-	-	47	51	47.66	0:21:36	48	51	49.8	0:23:04
20	5	-	-	46	48	46.2	0:29:58	49	50	49.5	0:27:53
	7	-	-	19	25	22	0:28:46	19	24	23.33	0:28:49
	3	-	-	35	40	36.2	0:32:16	35	39	37.8	0:30:10
40	5	-	-	34	37	35.6	0:38:36	36	40	39.6	0:39:23
	7	-	-	16	18	17.2	0:36:34	15	17	16.8	0:37:12
	3	-	-	70	86	72.2	0:37:45	69	73	71.2	0:36:19
60	5	-	-	55	61	56.6	0:38:44	58	64	63.6	0:40:55
	7	-	-	68	73	70	0:40:08	68	74	70.2	0:41:17

Table 23. RPD values and average execution times calculated.

AP	Runway	GA RPD	GA Average Computation Time (Sec)	ICA RPD	ICA Average Computation Time (Sec)
	3	0.00	0:00:16	0.00	0:00:14
4	5	0:00	0:00:17	0:00	0:00:17
	7	0:00	0:00:20	0:00	0:00:19
	3	0:00	0:00:30	0:00	0:00:30
6	5	0:00	0:00:37	0:00	0:00:33
	7	0:00	0:00:43	0:00	0:00:43
	3	0:00	0:01:21	0:00	0:01:47
10	5	0:06	0:02:33	0:06	0:02:29
	7	0:08	0:03:00	0:11	0:03:21
	3	0:01	0:21:36	0:04	0:23:04
20	5	0:004	0:29:58	0:01	0:27:53
	7	0:16	0:28:46	0:23	0:28:49
	3	0:03	0:32:16	0:03	0:30:10
40	5	0:05	0:38:36	0:10	0:39:23
	7	0:08	0:36:34	0:12	0:37:12
	3	0:03	0:37:45	0:03	0:36:19
60	5	0:07	0:38:44	0:10	0:40:55
	7	0:03	0:40:08	0:03	0:41:17

Statistical results indicate that GA performs better than the ICA algorithm. The mean plot with LSD intervals for the two algorithms is shown in *Fig. 8* for further analysis of the results. According to the tables above and the figure below, the values of the objective function and the execution time in both GA and ICA algorithms are close to each other. The GA algorithm performs better than the ICA algorithm in terms of both the value of the objective function and the execution time.

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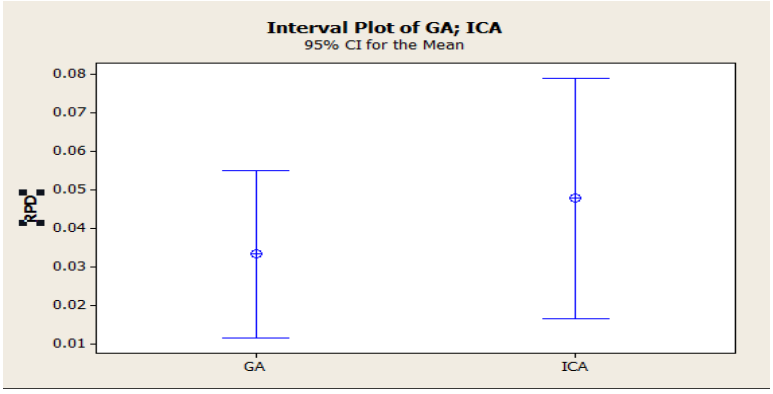

Fig. 8. Mean plot and LSD intervals (95% confidence level) for GA and ICA algorithms.

RPD values for different numbers of aircraft and runways are shown in *Figs. 9* and *10*.

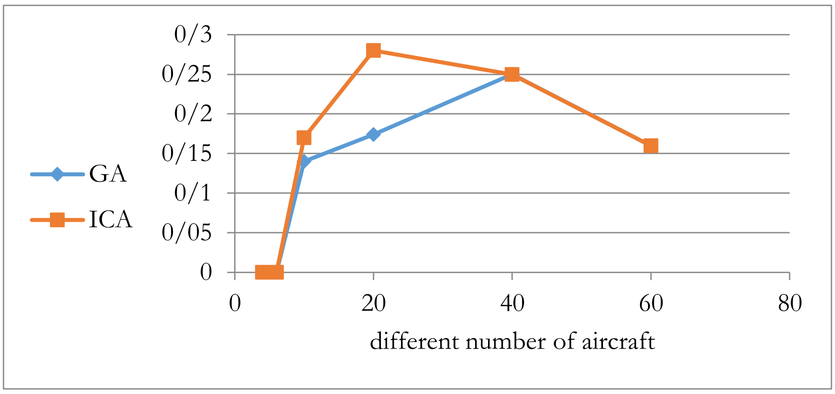

Fig. 9. RPD values for different number of aircraft.

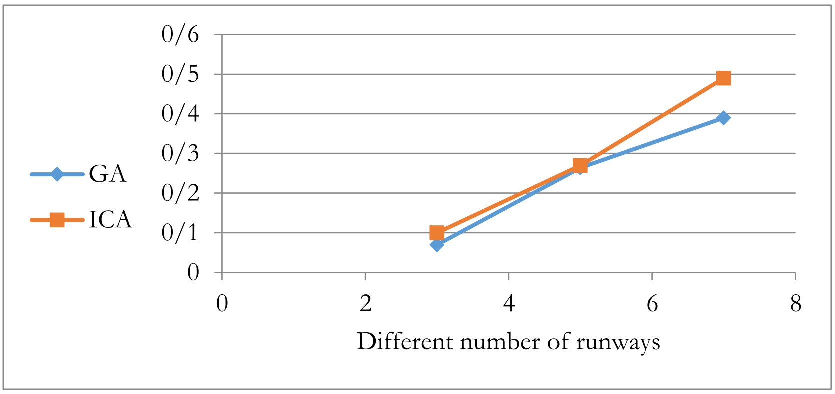

Fig. 10. RPD values for different number of runways.

As shown in *Figs. 9* and *10*, as the number of aircraft and runways increases, the difference between the performances of the two proposed algorithms is greatly reduced.

5 | Conclusion

This is conducted to solve the aircraft take-off and landing problem in situations where take-off and landing times are uncertain and aircraft also have access restrictions. It also considers the possibility of runway disturbances and the time required to repair the runway. None of the previous studies have examined the assumption of the possibility of runway disturbances, the time required to repair the runway, the lack of access to aircraft at certain times, and the uncertainty of take-off and landing times at the same time. On the other hand, finding the sequence of landing and take-off on runways to minimize the total delay and haste in take-off and landing of aircraft is one of the most difficult problems of combined optimization even on a medium scale. In this study, a new integer scheduling model for the flexible airline scheduling problem is provided to minimize the total weight of aircraft delays and haste considering constraints such as aircraft's ready time, runway disruptions, limited aircraft access, and runway access time. The computational difficulties of this problem have made it impossible to solve it accurately on a large scale. According to studies, this is an NP-hard problem even for airport scheduling mode, which becomes almost impossible to solve through precise methods and optimization software as the number of aircraft increases. So, the use of heuristic and meta-heuristic algorithms can be helpful. GA and ICA algorithms are used to solve the problem.

We first designed the corresponding mathematical programming model to solve the problem studied in this research work. Then, we presented the robust counterpart of the problem model using a robust planning approach. We solved the problem with certain and uncertain conditions and discussed several scenarios for parameters involved in the solution. Finally, we solved the problem using genetic and imperialist competitive algorithms concerning its complicated structure. For this purpose, we proposed the GA and imperialist competitive algorithm to solve this problem and employed different parameters for them.

Based on obtained results, the mathematical programming model can be solved in a shorter time and with sufficient accuracy. It is because that the data from the studied sample is such that we are not dealing with a large-scale problem at first, and metaheuristic algorithms cannot compete with the exact methods such as the branch and bound algorithm in terms of execution time and solution quality. Therefore, it is observed that the exact method solution is more accurate than that of the genetic and imperialist competitive algorithm employed in this study. But the results show the ability of algorithms which are applied to solve this model. The presented algorithm can provide acceptable solutions for problems, which cannot be solved by exact methods and different solvers such as CPLEX in a reasonable time.

In this study, the problem is investigated in terms of the number of aircraft and runways to evaluate the algorithms used. The results confirm the correct operation of the algorithms. According to the results, further studies are recommended to use accurate problem-solving methods such as the Benders decomposition algorithm or variable neighborhood descent meta-heuristic algorithm. It is also recommended that fuzzy theory and logic of gray numbers be used in the mathematical model and that the results be compared with this study.

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Prediction of Stress Concentration Factor in Butt Welding Joints Using Artificial Neural Networks

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Abstract

In welded constructions, there should be no defects in the welding seams, or defects should have in an acceptable range for obtaining more reliable welding operations. An undercut is one of the most important welding defects occurring on the workpieces produced by butt welding. Determining the correct value of the Stress Concentration Factor (SCF) allows deciding whether it accepts welding defects, in which case. Many characteristics and ranges influence SCF, making it challenging to calculate a more precise SCF. In this study, six different Artificial Neural Networks (ANNs) models are developed for predicting SCF. These models differ in terms of the training dataset used (70%-90%) and the number of neurons (5-10-20) in the hidden layer. Developed ANN models consist of three input variables the ratio of Undercut depth (h) and Undercut deep Radius (r), reinforcement angle (Q1), deep angle of welding seam (Q2), and an output variable as SCF. The prediction performance of 6 developed ANN models in different specifications is compared. The model with a 90% training set and five neurons in the hidden layer performed the best with an accuracy of 0.9834. According to the ANN model with these features, MAE, MAPE, and RMSE values are calculated as 0.0094, 2.50%, and 0.0129, respectively.

Keywords: Welding defects, Stress concentration factor, Artificial neural networks.

1 | Introduction

Welding operation is extensively used in almost every engineering structure, such as air vehicles, marine vehicles, ships, bridges, automobiles, buses, the piping industry, and pressure tanks [1]. Flexion, tension, and integrated fatigue loads, which cause the growth of cracks-like defects, generally affect welded connections. Defects common in welded joints can be classified as low diffusion of the weld, gas pores, undercutting at the weld toe, etc. Therefore, defects give rise to stress concentrations by the crack-like. The defects are usually placed at the weld toe [2]. Besides, residual stresses can occur in welded joints due to discordant thermal strains caused by increasing and decreasing temperature cycles. These stresses, called fatigue, also negatively affect the life of welded structures. Tensile residual stress of yield strength is located at the weld toe regions [3].

One of the most common welding faults caused by stress is undercutting. Defining the Stress Concentration Factor (SCF) is an essential milestone in the fatigue failure analysis of structures. The

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findings revealed that SCF and its associated factor, the fatigue notch factor (Kf), significantly impact the analyses. One of the results of stress concentration in welded components is weld discontinuities. Weld geometry parameters such as weld flank angle, weld throat, and weld toe radius also affect stress concentration [4].

While reviewing the literature, numerical and experimental studies are handled together and separately, as shown in the literature summary table (*Table 1*). In addition, studies using predictive models such as Artificial Neural Networks (ANNs), support vector machines, regression methods, Lagrangian interpolation methods, and Bayesian methods are few compared to numerical and experimental studies. In this study, the effect of different training set ratios and different neuron numbers used in the hidden layer on the forecasting performance of ANN, which is a powerful tool in prediction, has been investigated and aimed to fill the gap in the literature and to achieve stronger prediction success.

Table 1. Some studies in literature.

Reference	Year	Material	Method(s)	Prediction Performance	Numerical/ Experimental/ Prediction Model
Guo et al. [5]	2022	High-strength steel wires	Finite element method, Bayesian method	95%	Exp.+Pred.
Abbasnia et al. [6]	2021	Orthotropic plate	A new method based on regression analysis	99%	Num.
Makki et al. [7]	2018	Welded joints	Response surface models	NA	Num.
Li et al. [8]	2020	Cable steel wire	Finite element model	NA	Exp.
Wang et al. [9]	2020	Fillet weld joints	Parametric formula	NA	Num.
Jiang et al. [10]	2018	Multi-planar tubular DT-joints	Parametric equations	More than 80%	Num.
Dabiri et al. [4]	2017	T-welded joint	Neural network	99.99%	Pred.
Bajić et al. [11]	2017	Pipeline	Finite element method, 3D DIC method	NA	Exp.
Wang et al. [12]	2016	Cylindrical pressure vessels	Extreme learning machine	98.73%	Pred.
Ozkan and Toktas [13]	2016	Rectangular plate	Analytical model, regression analysis, finite element analysis, ANN	96.61%	Num.+Exp.+Pred.
Ji et al. [14]	2015	Corrosion pits	The least-squares support vector machine	NA	Pred.
Zappalorto and Carraro [15]	2015	Orthotropic composite plates	Analytical modeling	NA	Num.
Darwish [16]	2012	Isotropic plate with a circular hole	ANSYS parametric design language	94.4%-99.7%	Exp.
Cerit [17]	2013	Circular cylinder	3D stress analyses, torsion formula	NA	Num.+Exp.
Cerit et al. [18]	2010	Butt welded joint	Reinforcement metal in butt welded joint	99%	Num.+Exp.
Arola and Williams [19]	2002	AISI 4130 CR steel	Arola-Ramulu model	98.00%	Num.
Ida and Uemura [20]	1996	Fillet welded joint	Ushirokawas's and Tsuji's formulae	NA	Num.
Chang and Dover [21]	1996	Tubular X and DT joints	Parametric formulae and regression analysis	NA	Num.+Pred.
Guagliano et al. [22]	1993	Crankshaft	Bidimensional model	91.4%-93.1%	Num. + Exp.

Numerical and experimental analyses derive the results of numerous SCF investigations in the literature. There are few AI-supported investigations, and using current mathematical models and conducting

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experiments is complex and time-consuming. In addition, the studies have been carried out considering certain values of the parameters and require new analysis and calculations for different parameter values. ANN-based models with high prediction accuracy can process all possible experimental data quickly. The company aims to reduce the number of defects and errors caused by welding. When the stress concentration value in a significant part of the workpiece is exceptionally high, job safety decreases. Controlling the welding seam in welding constructions is critical in this regard. Due to the non-linear relationships between the parameters affecting the SCF value, one of the most effective ways to define SCF is through modeling. To get more effective results and reduce welding errors, a model is developed for SCF.

Numerous experiments are not required to comprehend the correlations between parameters because of the developed ANN model. Because ANN is a technique that does not require any machinery or equipment, numerous experiments, and can generate useful results. ANN is one of the most valuable methods of diversity areas for researchers [23]. Thus, it avoids the need for experimentation, assures that welding faults are identified beforehand, and lowers the rate of defective products, increasing job safety. Recent advancements in the field of ANN technology have helped overcome various issues in engineering procedures. Because of its effective prediction performance, the ANN technique is selecte for the prediction model of the SCF parameter, which is influenced by various parameters [24], [25].

Even when the parameters impacting the SCF value fluctuate, an ANN-based model is built into this work to calculate the SCF value without the requirement for long-term repeating tests. In this study, an ANN-based model was developed to determine the SCF value without requiring time-consuming, repetitive experiments even when the parameters affect the SCF value change. In addition, it has been investigated how constructing the ANN model with different training set ratios and the change in the number of neurons in the hidden layer used in the model is effective in estimating the SCF value.

In summary, the remaining sections of the research cover the following subjects. Section 2 discusses the structure and properties of the ANN model, as well as detailed information regarding SCF. The data is obtained, normalization procedures are performed, and the data is then integrated into the ANN model in Section 3. Then, the prediction performances of six ANN models are evaluated and compared in Section 4. By considering many statistical error types. Finally, the results and findings are included in the conclusions section.

2 | Methodology

2.1 | Stress Concentration Factor

According to experimental results, the stress concentration on welded sections is not uniform. There is no uniformity in manufacturing these elements due to cracks, voids, and other loads. Rarely, occurring stress could be tallied, unlike medial stress (F/A). Also, some sections' stress may be at the highest level. The notch effect occurs when the stress concentration level reaches its maximum value in particular areas, and this difference from the average value causes stress concentration. The change is depicted in *Fig. 1*.

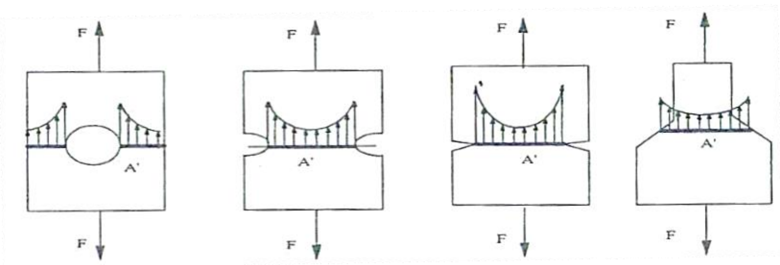

Fig. 1. View of notch sections cause stress concentrations in some tensile conditions.

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This situation is calculated mathematically as *Eq. (1)* where σ_{max} describes maximum stress, A' represents the cross-sectional area, and F is force.

$$\sigma_{\max} = \mathrm{SCF}\frac{\mathrm{F}}{\mathrm{A}'}. \tag{1}$$

In *Eq. (2)*, the cross-sectional area is stated as A' SCF is a coefficient of total stress loads called SCF. All along SCF value is bigger than 1. So SCF is a ratio of maximum regional stress (σ_{max}) to the average value (σ_{avg}) [7].

$$\mathrm{SCF} = \frac{\sigma_{\max}}{\sigma_{\mathrm{avg}}}. \tag{2}$$

2.2 | Artificial Neural Networks

ANN is a tool that has been developed inspired by neural networks in the human brain and is used to solve complex problems [4]. More than one artificial neuron interacts with each other in a hierarchical structure in ANN [26]. Different elements, such as cells and nodes, exist in this structure, apart from neurons. Some links show the relations of the nodes with each other. Each link has a weight and can be unidirectional or bidirectional. As in the solution algorithms of traditional programming, the step-by-step solution approach is replaced by a neural network structure that searches for a solution by itself according to the predetermined rules in ANN. This neural network structure generates new rules over time and compares the results from these rules with the sample data set results [27].

ANN offers a highly effective estimation for many values, including intermediate values for SCF, saving time and money over performing experiments for every value of each parameter in the input layer. However, the future addition of a new parameter, makes it simpler to analyze its impact. Without this model, numerous experiments would be required to add a single parameter.

ANN is architecturally composed of an input layer, a hidden layer (one or more), and an output layer [28]. The network is tested for the input and output layers. Then, the weights required to give the desired output are calculated. This calculation is called learning. Three different learning methods are used in ANN: supervised learning, unsupervised learning, and reinforcement learning, respectively. The purpose of learning is that the actual and ANN outputs are as close as possible. This value also determines the successful performance of the network.

In general, ANN is divided into feedforward and feedback networks according to the direction of information progression. The input layer, hidden layers, and output layer are in both groups. In feedforward networks, weights establish connections between neurons in the layers. Information moves unidirectionally from the input to the output layer [29]. There is no connection between units in the same layer in feedforward networks. However, neurons are interconnected and have dynamic memory in feedback networks. Due to the context layer in feedback networks, the hidden layer outputs are weighted back to the input layer and re-enter the hidden layer as input. Therefore, information also moves backward in these networks.

The backpropagation algorithm is one of the most used among many different learning algorithms in ANN. The backpropagation algorithm constantly compares the error rates of the actual values in the data set with the output values of ANN and updates the weights. If the output values exceed the desired value, the ANN returns to the previous step by changing the weight values [4].

The input layer, which contains problem-related parameters, gets data processing instructions from another cell or the outside. By summing the multiplication of the information received in the cell (X_1, X_2... X_n) and the weights of the cells (W_1, W_2... W_n), the sum function estimates the cell's net entry information [30]. *Eq. (3)* denotes the sum function where X_i is the value of input criteria and w_i is the weight. *Fig. 2* depicts the structure of ANN.

$$Net = \sum_{i=1}^{n} X_i \cdot w_i. \quad (3)$$

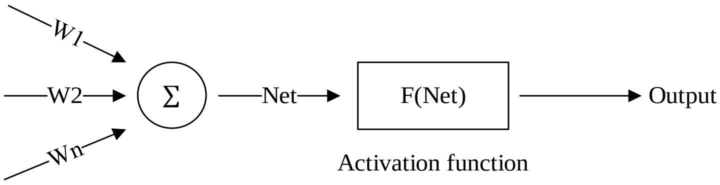

Fig. 2. The structure of ANN.

3 | Implementation

The parameters used in the model are determined within the scope of the study. After the data is obtained using ANSYS mechanical simulation software, data is normalized, and the ANN models are generated. The flow chart of the study is shown in *Fig. 3*.

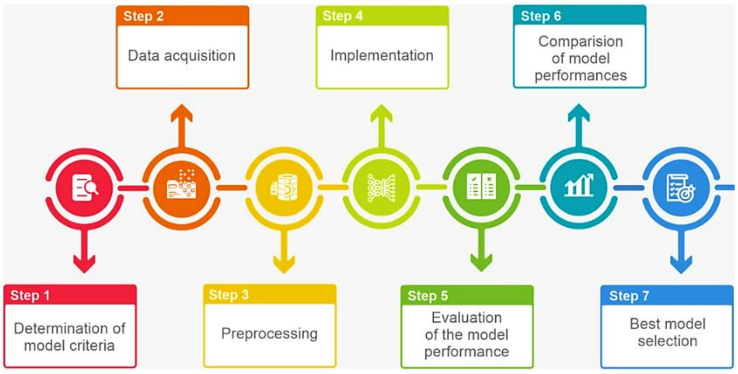

Fig. 3. Flow chart of the study.

3.1 | Data Acquisition

In this study, estimations are handled based on a V-welded workpiece. Undercut defects are common after an arc welding operation. *Fig. 4* shows the parameters that affect the undercut.

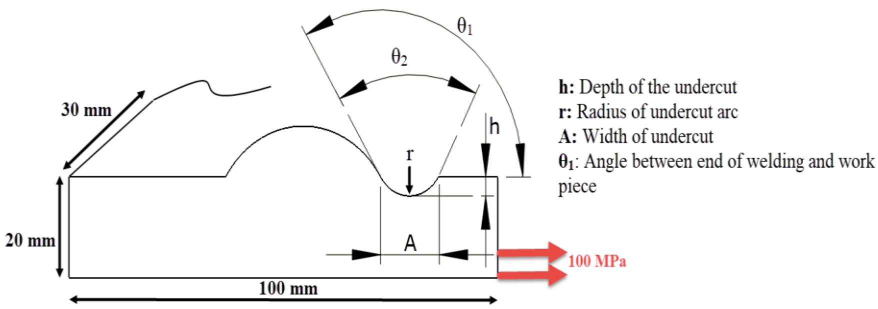

Fig. 4. Undercut sight of work piece.

The pressure value exposed to the workpiece from the front side to the undercut is 100 MPa. According to the parameters below *Table 2*, different workpieces are created as visuals and analyzed to obtain SCF values. A, R, h, and θ_1 are affecting parameters for SCF, and *Table 3* illustrates some of the experimental values for these parameters. These values are calculated using ANSYS Mechanical Simulation Software [18].

Table 2. Parameters of undercut.

h (mm)	θ_1 (degree)	An (mm)	r (mm)
0.5	120	3	0.5
1	140	4	1
1.5	160	5	1.5
2	180		
2.5			

Table 3. Experimental data values.

	h	$\sqrt{h/r}$	θ_1 = 180 SCF	θ_1= 160	θ_1= 140	θ_1=120
	0.5	1	2.83	3.14	3.3	3.36
	1	1.41	4.41	4.72	4.91	4.94
A:3 R:0.5	1.5	1.73	5.07	5.41	5.5	5.56
	2	2	6.08	6.27	6.34	6.41
	2.5	2.23	7	7.27	7.23	7.31
…	…	…	…	…	…	…
	0.5	0.57	2.04	2.17	2.37	3.48
	1	0.81	2.72	2.85	2.93	2.94
A:5 R:1.5	1.5	1	3.23	3.35	3.41	3.43
	2	1.15	3.74	3.83	3.88	3.89
	2.5	1.28	4.17	4.25	4.29	4.3

The data normalization procedure utilized in ANN effects positively trains the network [31]. As a result, the experimental data are normalized between 0 and 1 using *Eq. (4),* where X is the normalized data, X_i is the experimental data, X_{min} is the minimum value of experimental data and X_{max} is the maximum value of experimental data.

$$X = \frac{X_i - X_{min}}{X_{max} - X_{min}}. \quad (4)$$

3.2 | Developed ANN Models

This study develops six different ANN models for predicting SCF value. The training dataset used (70-90 percent) and the number of neurons in the hidden layer (5-10-20) differ among these models. Developed ANN models consist of three input variables (Undercut depth (h) / Undercut deep Radius (r)), reinforcement angle (Q1), and deep angle of welding seam (Q2), and an output variable as SCF.

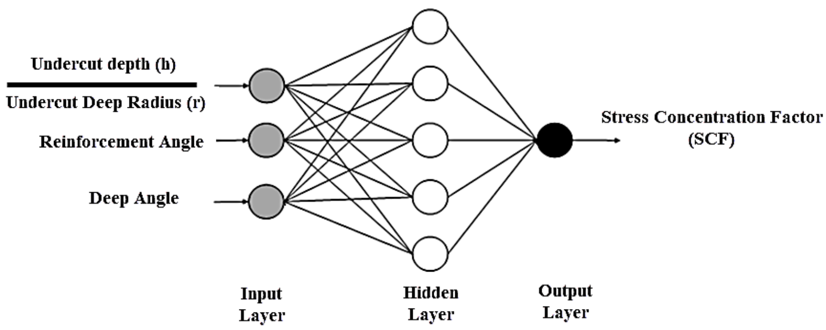

Fig. 5. ANN topology of proposed models.

ANN models have three input layers, a hidden layer, and an output layer, shown in *Fig. 5* as a topology of models. The features of the developed ANN model are given in *Table 4*.

Table 4. Architecture and functions of the implemented ANN.

Network	Feedforward Backpropagation Network
Training function	Levenberg-Marquardt
Learning function	Gradient descent with momentum weights and bias learning function
Transfer function	Tan sigmoid & Linear transfer function
Performance function	Mean squared error
Training dataset rate	70%-90%
Number of neurons in the hidden layer	5-10-20

4 | Statistical Analysis

The prediction performances of the models are compared by calculating MAE, MAPE, RMSE, and R^2 values. According to the results, the prediction performance of the ANN model developed using a training set ratio of 90% and including five neurons in the hidden layer is better. Forecast performances are calculated with the following formulas *Eq. (5-8)* to indicate A_t actual values F_t predicted values. *Table 5* is obtained with the help of the following formulas by comparing the experimental data with the results of the ANN model predictions.

$$\mathrm{MAE} = \frac{1}{n}\sum_{t=1}^{n} |A_t - F_t|. \tag{5}$$

$$\mathrm{MAPE} = \frac{1}{n}\sum_{t=1}^{n} \frac{|A_t - F_t|}{|A_t|} \mathrm{x}100. \tag{6}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(A_t - F_t)^2}. \tag{7}$$

$$R^2 = 1 - \frac{\sum_{t=1}^{n} A_t - F_t)^2}{\sum_{t=1}^{n}\left(\overline{A_t} - A_t\right)^2}. \tag{8}$$

Table 5. Prediction performance of the models.

Training set ratio	Number of Neurons in the Hidden Layer	MAE	MAPE	RMSE	R2
70%	5	0.0238	10.87%	0.0318	0.9761
	10	0.0312	16.78%	0.0481	0.94
	20	0.0596	22.42%	0.0955	0.8788
90%	5	0.0094	2.50%	0.0129	0.9834
	10	0.0243	9.25%	0.0328	0.9818
	20	0.0390	9.95%	0.0733	0.8157

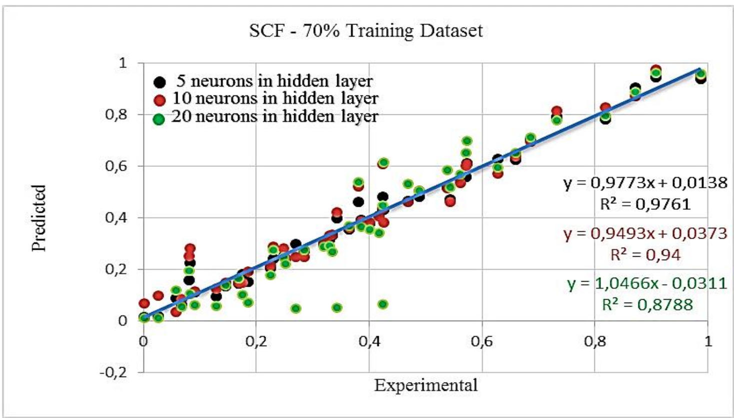

Fig. 6. 70% training dataset used ANN models.

The blue line represents the experimental (real) data, while the hidden layer's black, red, and green dots indicate 5-10-20 neurons in *Fig. 6* and *Fig. 7*, respectively. The prediction performances of three constructed ANN models are calculated using linear regression analysis and mean square errors. It is clear that the prediction performance of the ANN model, which includes five neurons and is trained with both 70% and 90% of the dataset, produces the most realistic and effective results based on the SCF value.

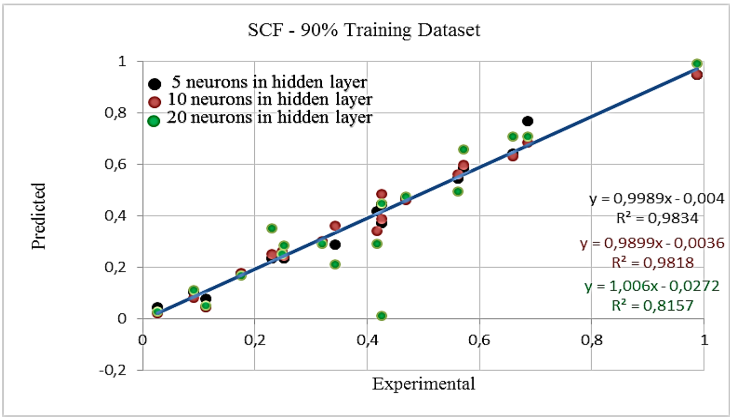

Fig. 7. %90 training dataset used ANN models.

5 | Conclusions

For more reliable welding operations, there should be no defects in the welding seams or within an acceptable range in welded constructions. The undercut is one of the most common welding flaws found on workpieces generated by butt welding. When the SCF value is determined, it is possible to decide whether to accept welding flaws in the case. SCF is influenced by a wide variety of parameters and their ranges, making it difficult to calculate a more precise SCF. Due to the many costs and limits of experiments, including the necessity for qualified personnel, repeat studies are extremely challenging. Traditional models struggle to address problems with such a complex structure. Thus, ANN is frequently used in modeling complex systems, providing good estimate performance between prediction models.

In this study, considering the calculation complexity of SCF, six ANN models are developed that differ in terms of the number of neurons in the hidden layer and the percentage of the training dataset. 6 ANN models, which include three input layers (Undercut depth (h) / Undercut deep Radius (r)), reinforcement angle (Q1), and deep angle of welding seam (Q2), a hidden layer which included three different numbers of neurons (5-10-20) and an output layer as SCF. 70% and 90% of the dataset is used for the training process of ANN models. Prediction performances of 6 developed ANN models are compared statistically. The best prediction performance is obtained with the 90% training dataset and five neurons in the hidden layer (R^2=0.9834). This value demonstrates that the SCF value may be obtained with good estimation performance without the requirement for experimentation and with a more cost- and time-effective use of laboratory resources. However, it is possible to determine the result of even a minor modification rapidly and accurately in any parameter. The two developed ANN models, which include five neurons in the hidden layer, are trained with 70% and 90% training datasets and are most effective in predicting SCF value. The increasing number of neurons in the hidden layer is found to have a negative impact on the prediction performance of ANN models. Therefore, studies can be made on the optimum number of neurons in the hidden layer between 5-10.

Compared to numerical and experimental studies, there are few studies on welding prediction models. It is crucial to thoroughly evaluate the situation and build the properly ANN model while building a prediction model. Good results are likely to be attained with a properly built model, saving time on experiments. The findings of the current study support that, in contrast to previous estimation studies for using specific parameter values, high estimation accuracy may be achieved by using all parameter values. The resulting predictions and the numerical experiment results are in good agreement with

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testing examples, indicating the remarkable performance of ANN in the prediction of SCF of butt welding. Finally, numerous quantitative evaluations based on statistical error types validate the accuracy and effectiveness of the presented ANN predicting method.

The findings of this study enable effective welding error reduction without the need for experimentation. It makes suggestions for the research to be conducted in increasing job safety so that a useful result can be obtained in less time and at a lower cost. It should be mentioned that the model of this study is only applicable for variables that affect SCF. However, the proposed approach also provides a workable framework for additional problems. Machine learning techniques could also be employed with many parameters and experiments in future works.

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Identification and Evaluation of Congestion in Two-Stage Network Data Envelopment Analysis

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Abstract

Congestion is one of the important concepts in data envelopment analysis that occurs when excessive inputs reduce the maximally possible outputs. Identification and elimination of congestion have a significant impact on reducing inputs along with increasing outputs. Hence, various studies have been conducted to detect and evaluate congestion. However, in today's world, no organization can achieve its final output with just one process of input. In other words, today's organizations have a network structure that consists of several subsections. Ignoring the existing influences among the subsections processes may lead to inadequate or even incorrect results for evaluating the congestion. While all of the existing methods only evaluate the congestion of each subsection or the whole system independently. Therefore, in this paper, the concept of congestion is developed for a specific and so practical case of network structure called "two-stage network structure". This case of network structure consists of two series stage such that Stage 1 consume some primary inputs to produce some intermediate outputs. In the following, the intermediate outputs are used as the inputs of Stage 2 to produce the final output. Here, the concept of congestion is defined for systems with a two-stage structure. Then, to examine the congestion of each stage as well as the congestion of the whole system, a single linear programming model is proposed. The validity of the proposed model is investigated using several theorems and it is shown that the new definition is a generalization of the previous definitions of the congestion for the black-box systems. Finally, the proposed model is applied to a case study including 24 non-life insurance companies in Taiwan.

Keywords: Network data envelopment analysis, Two-stage network structure, Intermediate output, Congestion.

1 | Introduction

Congestion is an important concept in data envelopment analysis that can be effective in improving the efficiency of decision-making units. Evaluating the efficiency of homogenous decision-making units is the primary goal of data envelopment analysis models. The efficiency of these units is affected by the number of resources they consume. On the other hand, an increase in input is often accompanied by an increase in output. But this is not the case in all production technologies. In other words, sometimes increasing the input sources leads to decreasing the output, and that is the concept of congestion. For example, increasing the number of workers in a mine causes them to collide with each other, thus reducing output.

Input congestion is a special case of inefficiency in which reducing at least one of the input components (without increasing the other input components) can increase at least one of the output

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components (without decreasing the other output components). It should be noted that this type of inefficiency or technical inefficiency is already known and different methods and models in data envelopment analysis can be used to distinguish it from other forms of inefficiency for example [1] Identifying, evaluating, and eliminating congestion can lead to useful results in real-world applications, such as cost reduction and increased output.

The concept of congestion was first investigated by Färe and Svensson [2], and then, its more complete version was presented by Färe and Grosskopf [3] and Färe et al. [4]. Their model calculates the congestion impact as a ratio of the observed amounts to the expected amounts. However, it only detects the presence or absence of congestion and may sometimes reach incorrect results. In another study, Cooper et al. [5] proposed a slack-based approach to calculate the congestion impact as the difference between the observed amounts and the expected amounts. This approach has some strong points to the previous method. It determines the congested inputs and provides the amount of congestion in each input. In the following, Cooper et al. [6] expanded a unified additive model using additive models for determining congestion. Later, Cooper et al. [1] proposed a single model to assess congestion without solving two models similar to previous methods. Brockett et al. [7] developed a model known as the "BCSW" based on the proposed method by Cooper et al. [6]. By determining input congestion, Jahanshahloo and Khodabakhshi [8] introduced a suitable combination of inputs for improving outputs. Moreover, other studies by Wei and Yan [9] simultaneously studied congestion and different types of returns to scale using the DEA output-oriented models. They also recognize the necessary and sufficient conditions for the evidence of congestion and different kinds of returns to scale. Sueyoshi and Sekitani [10] proposed a method that can detect congestion in the presence of multiple solutions.

In general, studies on congestion in the DEA framework are important in two aspects. These two aspects are the identification and measurement of congestion. Congestion identification methods have been in development for nearly 4 decades. The first study in this field was conducted by Färe and Svensson [2] in which they explained that congestion occurs when increasing some of the inputs may decrease the outputs. In the following, Färe and Grosskopf [3] pointed out that the reason for the neglect of congestion may be attributed to the assumption that isoquants have no positive slope anywhere. Accordingly, Färe et al. [4] broke this assumption by creating a positive slope isoquants assuming weak disposability of inputs. They proposed the FGL method for congestion identification. Cooper et al. [11] provided a numerical example to show that the FGL method cannot identify congestion well. Due to the shortcomings of the FGL method, Cooper et al. [5] proposed the CTT method based on the strong disposability assumption of inputs. Then, Wei and Yan [12] and Tone and Sahoo [13] proposed the WY-TS method to identify congestion. This method constructs a Production Possibility Set (PPS) for identifying congestion by removing the disposability assumption of inputs. Noura et al. [14] proposed a new method to reduce the computational effort required for calculating congestion. Sueyoshi and Sekitani [15] pointed out that the WY-TS method did not consider the existence of multiple optimal solutions, and this issue may reduce the stability of the WY-TS method in identifying congestion. Mehdiloozad et al. [16] proposed the MZS method to improve this shortcoming of the WY-TS method. On the other hand, from a measurement point of view, it should be noted that congestion refers to the reduction in outputs caused by excessive inputs. Therefore, both the excessive inputs and reduction in outputs can reflect the measure of congestion. For example, the FGL method proposed by Färe et al. [4] uses the amount of excessive input as an indicator to measure the degree of congestion; the WY-TS method proposed by Wei and Yan [12] and Tone and Sahoo [13] uses the output reduction caused by congestion to measure the degree of congestion.

In recent years, various studies have been conducted to develop the concept of congestion in data envelopment analysis. For example, Karimi et al. [17] proposed a method that evaluates the congestion in integer-valued DEA. Khoveyni et al. [18] investigated the recognition of congestion in the presence of negative data and specified the least and the most congested DMUs. Shabanpour et al. [19] proposed a novel DEA model to show that an increase in congested inputs may lead to higher outputs/efficiency. Moreover, they used the concept of input congestion as a tool for ranking decision-making units. Adimi

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et al. [20] introduced the concept of congestion hyperplane without considering the efficiency value. Salehi et al. [21] presented a new method to identify congestion based on the definition of congestion. Xian-ton Ren et al. [22] innovatively tried to eliminate congestion by increasing inputs in the case of R&D activities of Chinese universities. They also analyzed the relationship between congestion and overinvestment. Navidi et al. [23] represented the method that measures congestion without solving a model. Yang et al. [24] proposed the concept of directional congestion in the framework of data envelopment analysis. Velázquez and Benita [25] investigated the patterns and dynamics of efficiency, productivity, and technological change of the automotive sector in Mexico. Cho and Yang [26] developed a new method for congestion analysis based on the slacks-based measure approach that keeps a close link between undesirable outputs, desirable outputs, and inputs. According to the S-shape form of the production function and concerning the geometric features of the anchor point, Shadab et al. [27] developed an algorithm by the connection between the anchor points and congestion definition. Khoshroo et al. [28] used the Bounded Adjusted Measure (BAM) to improve the efficiency of tomato production as well as decrease the carbon footprint. Fallahnejad et al. [29] considered the effect of input congestion on cost inefficiency and presented a new decomposition of cost efficiency and observed cost versus optimal cost.

In addition to the aforementioned studies, there are various methods to recognize the evidence of congestion. But the remarkable point in all of these methods is the lack of attention to the internal structure of the decision-making units. In other words, existing methods identify and evaluate congestion without considering the internal structure or the existing communication between the stages. However, nowadays, the complexity of goods or services is such that few organizations or institutions can produce products alone and without cooperation with other organizations. This disregard for the influences between the stages may lead to inadequate or even incorrect results.

Here, a real example is provided for further explanation. Suppose we are looking to evaluate a factory that produces wood products such as tables, chairs, sofas, etc. The factory uses raw materials such as human resources, costs, and raw wood. The factory also has a fixed area for equipment installation and storing of raw materials and production. In the first stage of this factory, the input woods are converted into different types needed for construction in the next stage. This stage includes the cutting and processing work required for the next stage. In the second stage, by using the products of the first stage (e.g. table, chair, sofa) and the specialized human resources, the final products are provided. Now, if this factory has too much manpower or raw materials for wood, this will cause congestion. Because the presence of too much manpower causes confusion and disruption in the work and the presence of too much raw wood occupies the space needed to perform other activities. The same is true for the wood produced in the first stage. Overproduction of processed wood in the first stage may reduce final production by occupying the workspace and disrupting other tasks.

The aforementioned example is a sample of a system with a two-stage network structure in which the outputs of the first stage (called intermediate products) appear in the role of inputs of the second stage. Many practical problems can be modeled in today's world according to the two-stage network structures. For example, Zuo et al. [30] used a two-stage DEA model to construct indicators to measure Chinese provinces Mining Technological Innovation Efficiency (MTIE), Mining Eco-Efficiency (MEE), and Mining Comprehensive Efficiency (MCE). Silva et al. [31] addressed how socioeconomic conditions influence entrepreneurship-based activities in 18 European countries grouped into subregions (North, South, East, and West) during the period 2008–2018. They conducted their empirical study under a two-stage DEA model. Jingxin et al. [32] constructed a two-stage DEA model to measure Urban Construction Land Use (UCLU) efficiency. Henriques et al. [33] analyzed 59 papers and divided them into ten classes that cover various perspectives of two-stage DEA studies, such as the economic context, geographic region of the banking units, methodological characteristics, and type of the models, either internal or external. Chen et al. [34] proposed an extended two-stage network DEA approach for measuring the operating efficiency of 52 Chinese universities. Izadikhah et al. [35] developed a novel fuzzy chance-constrained two-stage data envelopment analysis model. Mozaffari and Ostovan [36] presented a two-stage supply chain with random data and the CRA model with ratio data used to calculate the projection of DMUs. Marzband

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[37] investigated the efficiency of supply chains in manufacturing and industrial companies. Nematizadeh and Nematizadeh [38] introduced a two-stage feedback structure including undesirable factors. Then, by applying the assumption of weak disposability for undesirable factors, they provided a method for analyzing the relative performance of such network structures.

To the best of our knowledge, all of the existing methods only evaluate the congestion of each stage or the whole system independently. GholamAzad and Pourmahmoud [39] have proposed a new method for measuring congestion in stages of the network. However, this method also does not examine the congestion in the whole system. Moreover, they have not theoretically discussed the proposed model. Accordingly, the current paper tries to develop the existing methods to identify and evaluate the congestion in decision-making units with a series two-stage network structure. To this end, a single linear model is presented that examines the possible congestion in each of these stages and the whole system by considering the congestion relationship between the stages and the whole system. The proposed model can be considered an extension of Cooper et al. [1] one-model method. Therefore, the main contribution of this paper is proposing the first valid method to identify and evaluate the congestion in the two-stage network structure.

The rest of the paper is organized as follows: Section 2 contains the required concepts and definitions, along with a brief description of the one-model method proposed by Cooper et al. [1]. In Section 3, the new model is proposed to detect and evaluate the congestion of the DMU with the series two-stage network structure. Section 4 provides a small numerical example to show the efficiency of the proposed model. Moreover, a case study of Taiwanese non-life insurance companies is conducted in this section. Finally, Section 5 concludes this research.

2 | Background

In this section, some required concepts and definitions of data envelopment analysis and network data envelopment analysis are presented. The first subsection includes the managerial implications and the second subsection presents the model proposed by Cooper et al. [1] to detect and evaluate the congestion in the black-box view.

2.1 | Managerial Implications

DEA is a non-parametric methodology for measuring the efficiency of homogenous DMUs that use multiple inputs to produce multiple outputs. On the other hand, Productivity is one of the basic concepts in management, which includes efficiency and effectiveness. There are various definitions of efficiency, effectiveness, and productivity. For example, Pritchard [40] illustrated three definitions related to productivity as follows:

I. Productivity is output/input or in other words, is a measure of efficiency.
II. Productivity is a composition of effectiveness and efficiency.
III. Productivity is referred to the broader concept that whatever makes the organization has a better function.

What is certain, however, is that productivity can be considered a function of efficiency and effectiveness. Where efficiency is interpreted as “Doing things right” and effectiveness is interpreted as “doing the right things”. The relationship between these three concepts can be seen in *Fig. 1*:

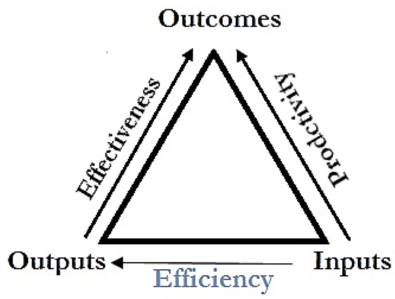

Fig. 1. The relationship between efficiency, effectiveness, and productivity.

Indeed, each DMU consumes the inputs to produce the outputs to achieve the outcomes. Meanwhile, the manager of DMU tries to produce maximum outputs by consuming minimum inputs. With these explanations, a DMU is productive if it works efficiently and if its master DMU has been planned effectively [41]. Therefore, the efficiency of the DMUs is evaluated to quantify their contribution to productivity.

To measure the efficiency of DMUs, DEA constructs the PPS by using some postulates. Then, the efficiency values of the DMUs are calculated relative to the frontier of PPS.

Definition 1. A DMU is efficient if no other DMU in PPS produces the same or more output by using the same or less input. In this way, technical inefficiency occurs when some input or output components can be improved without worsening other components.

In the meantime, a special type of inefficiency should be given more attention. This type of inefficiency is known as congestion. Identification and elimination of congestion have a significant impact on reducing inputs along with increasing outputs.

Definition 2. Input congestion occurs when an increase in one/more input components results in a decrease in one/more output components (without improving other input and output components); or conversely, a decrease in one/more input components results in an increase in one/more output components (without worsening other input and output components) [1].

Remark 1: although congestion can be considered a special case of technical inefficiency, it should be noted that congestion appears and is discussed in the DMUs in which the principle of input possibility is not established. In other words, by increasing the inputs of these DMUs, one cannot find a unit in the set that produces the same output. On the other hand, some technically inefficient DMUs (which do not meet this requirement and, of course, do not have congestion) may be true in *Definition 2* and be mistaken for congestion. Therefore, to prevent such errors, it is better to modify *Definition 2* For this purpose, it can be stated in *Definition 2* that there should be no DMU with more input/output related to the DMU under evaluation.

Definition 3. As mentioned, the concept of input congestion is discussed on the PPSs that lack the principle of input possibility. This set includes all DMUs that can produce the output vector Y by using the input vector X, considering the four principles: inclusion of observations, convexity[1], output possibility[2], and the principle of minimum interpolation. Such a production possibility set for n observed decision-making units, i.e. $DMU_j = (X_j, Y_j)$, $j = 1, \dots, n$, will be as the *Relation (1):*

[1] The convexity principle states that any weighted average (convex combination) of feasible production plans is feasible as well [42].

[2] According to the output possibility principle, if a unit (x, y) belongs to PPS, then any semi-positive $(x, \bar{y})$ with $y \le \bar{y}$ is included in PPS.

$$T=\left\{(X,Y)\mid \sum_{j=1}^{n}\lambda_j X_j = X, \sum_{j=1}^{n}\lambda_j Y_j \geq Y, \sum_{j=1}^{n}\lambda_j = 1, \ \lambda_j \geq 0 \ , j=1,\dots,n\right\}. \tag{1}$$

Definition 4. The decision-making unit with a series two-stage network structure refers to a unit that itself consists of two stages, according to *Fig. 2*. In such a unit that produces the output vector Y using the input vector X, there are some intermediate productions called the vector Z that is the output vector of the first stage. In other words, in such units, to generate the final output Y, the main input vector X is first provided to the first stage to generate the output Z. Then, the output vector of the first stage is given to the second stage as the input vector to generate the final output vector Y.

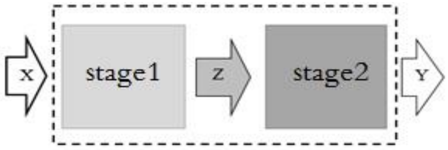

Fig. 2. DMU with two-stage series network structure.

The PPS for n observed DMUs, i.e. $DMU_j=(X_j, Z_j, Y_j)$, with the series two-stage network structure, is as the *Relation (2)*:

$$T=\left\{(X,Z,Y) \ \middle| \ \begin{array}{l}\sum_{j=1}^{n}\lambda_j X_j \leq X, \sum_{j=1}^{n}\lambda_j Z_j \geq Z, \sum_{j=1}^{n}\mu_j Z_j \leq Z, \sum_{j=1}^{n}\mu_j Y_j \geq Y, \\ , \sum_{j=1}^{n}\lambda_j = 1, \sum_{j=1}^{n}\mu_j = 1, \lambda_j \geq 0, \mu_j \geq 0 \ j=1,\dots,n\end{array}\right\}. \tag{2}$$

Note that the PPS in *Relation (2)* is constructed by considering the principles of input and output possibility. By removing the principle of input possibility, the PPS is changed as the *Relation (3):*

$$T=\left\{(X,Z,Y) \ \middle| \ \begin{array}{l}\sum_{j=1}^{n}\lambda_j X_j = X, \sum_{j=1}^{n}\lambda_j Z_j \geq Z, \sum_{j=1}^{n}\mu_j Z_j = Z, \sum_{j=1}^{n}\mu_j Y_j \geq Y, \\ , \sum_{j=1}^{n}\lambda_j = 1, \sum_{j=1}^{n}\mu_j = 1, \lambda_j \geq 0, \mu_j \geq 0 \ j=1,\dots,n\end{array}\right\}. \tag{3}$$

2.2 | Detection and Evaluation of Congestion in Black-Box View

As mentioned in the first section, several methods exist to identify and evaluate congestion. In the following, the proposed method by Cooper et al. [1] is briefly reviewed to detect and evaluate the congestion. They developed a one-model method by using the BCSW method [7] and combining its two models. To better explain, suppose that $X_j=(x_{1j},\dots,x_{ij},\dots,x_{mj})^T$ and $Y_j=(y_{1j},\dots,y_{rj},\dots,y_{sj})^T$ are the input and output vectors of DMU_j (j=1,…,n), respectively. Then, the proposed model by Cooper et al. [1] to detect and evaluate the congestion of DMU_O is as the *Model (4)*:

$$\begin{aligned} \text{Max} \quad & \varphi + \varepsilon\left(\sum_{r=1}^{s} s_r^{+} - \varepsilon \sum_{i=1}^{m} s_i^{-c}\right), \\ \text{s.t.} \quad & \sum_{j=1}^{n}\lambda_j x_{ij} + s_i^{-c} = x_{io}, \quad i=1,\dots,m, \\ & \sum_{j=1}^{n}\lambda_j y_{rj} - s_r^{+} = \varphi y_{ro}, \quad r=1,\dots,s, \\ & \sum_{j=1}^{n}\lambda_j = 1, \ \lambda_j \geq 0, \quad j=1,\dots,n, \\ & s_i^{-c}, s_r^{+} \geq 0, \quad i=1,\dots,m, r=1,\dots,s. \end{aligned} \tag{4}$$

Where ε is a small positive non-Archimedean value. Note that the presence of ε in *Model (4)* indicates the optimizing priority of the variables in the objective function. In fact, in this model, at the first, the variable φ is maximized, and then the variables $s_r^+(r=1,...,s)$ and $s_i^{-c}(i=1,...,m)$ are maximized and minimized, respectively.

Theorem 1. DMU_o has input congestion when the optimal solution of *Model (4)*, i.e., $(\varphi^*, \lambda^*, S^{-c*}, S^{+*})$, holds at least one of the following conditions [1]:

- $\varphi^* > 1 \text{ and } \sum_{i=1}^{m} s_i^{-c*} > 0.$
- $\sum_{r=1}^{s} s_r^{+*} > 0 \text{ and } \sum_{i=1}^{m} s_i^{-c*} > 0.$

Accordingly, the amount of congestion in i-th input will be determined by the value of s_i^{-c*}.

Theorem 2. Suppose that $(\varphi^*, \lambda^*, S^{-c*}, S^{+*})$ is an optimal solution of *Model (4)*. Then, DMU_o is inefficient if at least one of the following conditions occurs [1]:

I. $\varphi^* > 1.$

II. $\sum_{r=1}^{s} s_r^{+*} > 0$.

III. $\sum_{i=1}^{m} s_i^{-c*} > 0.$

Conversely, if $\varphi^* = 1$, $\sum_{r=1}^{s} s_r^{+*} = 0$ and $\sum_{i=1}^{m} s_i^{-c*} = 0$, then DMU_o is on the (efficient or inefficient) frontier of PPS defined in the *Relation (1)*.

Lemma 1 (Identification and evaluation of congestion in series two-stage network structure). Consider n observed decision-making units $DMU_j = (X_j, Z_j, Y_j)\ (j=1, ..., n)$, with the series two-stage network structure, where $X_j = (x_{1j},...,x_{ij},...,x_{mj})^T$, $Z_j = (z_{1j},...,z_{tj},...,z_{pj})^T$ and $Y_j = (y_{1j},...,y_{rj},...,y_{sj})^T$. Suppose the aim is to identify and evaluate the congestion of each stage and DMU_o as a whole, according to the proposed approach by Cooper et al. [1]. Therefore, the congestion assessment models for the first stage, the second stage, and the whole unit can be written as *Models (5)*, *(6)*, and *(7)*, respectively:

$$
\begin{aligned}
\text{Max} \quad & \varphi_1 + \varepsilon\left(\sum_{t=1}^{p} d_{1,t}^{+} - \varepsilon\sum_{i=1}^{m} s_{1,i}^{-}\right), \\
\text{s.t.} \quad & \sum_{j=1}^{n} \lambda_j x_{ij} + s_{1,i}^{-} = x_{io}, \qquad i = 1,...,m, \\
& \sum_{j=1}^{n} \lambda_j z_{tj} - d_{1,t}^{+} = \varphi_1 z_{to}, \qquad t = 1,...,p, \\
& \sum_{j=1}^{n} \lambda_j = 1,\ \lambda_j \geq 0, \qquad j = 1,...,n, \\
& s_{1,i}^{-}, d_{1,t}^{+} \geq 0, \quad i = 1,...,m, t = 1,...,p.
\end{aligned}
\tag{5}
$$

$$\begin{aligned}
\text{Max} \quad & \varphi_2 + \varepsilon\left(\sum_{r=1}^{s} s_{2,r}^{+} - \varepsilon\sum_{t=1}^{p} d_{2,t}^{-}\right), \\
\text{s.t.} \quad & \sum_{j=1}^{n} \mu_j z_{tj} + d_{2,t}^{-} = z_{to}, \quad t=1,\dots,p, \\
& \sum_{j=1}^{n} \mu_j y_{rj} - s_{2,r}^{+} = \varphi_2 y_{ro}, \quad r=1,\dots,s, \\
& \sum_{j=1}^{n} \mu_j = 1,\ \mu_j \geq 0, \quad j=1,\dots,n, \\
& s_{2,r}^{+}, d_{2,t}^{-} \geq 0, \quad r=1,\dots,s, t=1,\dots,p.
\end{aligned} \tag{6}$$

Models (5) and *(6)* detect the existing congestion of the first and second inputs separately, respectively. It should be noted that according to the design of the objective function in both models, three steps must be taken to solve these models. In the first step, the output-oriented radial image of the stage under evaluation is identified on the PPS. In the second step, the maximum non-radial improvement of all outputs is suggested on PPS. In the last step, the amount of congestion in each of the inputs is calculated. It should be noted that *Model (5)* corresponds to the PPS made by the first stage of DMUs but the PPS corresponding to *Model (6)* is made by the second stage of DMUs.

According to a similar idea, *Model (7)* can be proposed to calculate the congestion at the inputs of the network structure. This model similarly first specifies the output-oriented radial image of the network on the PPS. Note that here the PPS is constructed by the networks in the form of a black box, regardless of the intermediate productions. Then, the maximum non-radial improvement of all final outputs is suggested on PPS and at the end, the congestion is calculated in each of the primary inputs.

$$\begin{aligned}
\text{Max} \quad & \varphi + \varepsilon\left(\sum_{r=1}^{s} s_{r}^{+} - \varepsilon\sum_{i=1}^{m} s_{i}^{-c}\right), \\
\text{s.t.} \quad & \sum_{j=1}^{n} \gamma_j x_{ij} + s_{i}^{-c} = x_{io}, \quad i=1,\dots,m, \\
& \sum_{j=1}^{n} \gamma_j y_{rj} - s_{r}^{+} = \varphi y_{ro}, \quad r=1,\dots,s, \\
& \sum_{j=1}^{n} \gamma_j = 1,\ \gamma_j \geq 0\ , \quad j=1,\dots,n, \\
& s_{i}^{-c}, s_{r}^{+} \geq 0, \quad i=1,\dots,m, r=1,\dots,s.
\end{aligned} \tag{7}$$

Now according to *Models (5)*, *(6)*, and *(7)* and *Theorem 1*, the congestion in the first and second stages of DMU_o along with the congestion of DMU_o as a whole can be identified through *Theorems 3*, *4* and *5*, respectively:

Theorem 3. The first stage of $DMU_o = (X_o, Z_o, Y_o)$ exhibits congestion when at least one of the following conditions is met for the optimal solution of *Model (5)*, i.e., $(\varphi^*, \Lambda^*, S^{-*}, D^{+*})$:

I. $\sum_{i=1}^{m} s_i^{-*} > 0$ and $\varphi^* > 1$.

II. $\sum_{i=1}^{m} s_i^{-*} > 0$ and $\sum_{t=1}^{p} d_t^{+*} > 0$.

Proof: suppose that at least one of Cases 1 or 2 holds. Therefore, according to the constraints of *Model (5)*, the *Relation (8)* holds:

$$\begin{aligned}
&\sum_{j=1}^{n}\lambda_j^* x_{ij} = x_{io} - s_{1,i}^{-*} \le x_{io}, \quad i=1,\dots,m,\\
&\sum_{j=1}^{n}\lambda_j^* z_{tj} = \varphi_1^* z_{to} + d_{1,t}^{+*} \gneqq z_{to}, \quad t=1,\dots,p,\\
&\sum_{j=1}^{n}\lambda_j^* = 1,\ \lambda_j^* \ge 0, \quad j=1,\dots,n.
\end{aligned} \tag{8}$$

Now, according to the *Relation (8)* and the convexity principle, $(\sum_{j=1}^{n}\lambda_j^* X_j, \sum_{j=1}^{n}\lambda_j^* Z_j)$ is a member of *PPS (1)* corresponding to the first stages $(X_j, Z_j),\ j=1,\dots,n$, which can produce an output greater than Z_o (at least in one component) without worsening the input X_o. This means that the first stage of DMU_o, i.e. (X_o, Z_o), exhibits congestion compared to the first stages of other systems.

In this case, the amount of congestion in ith input can be achieved by the value of s_i^{-*} obtained from *Model (5)*. As a managerial interpretation of *Theorem 3*, if Case 1 of this theorem is established, then decreasing the components of input X will increase all components of output Z; and, if Case 2 holds, it means that a decrease in components of input X causes an increase in at least one components of output Z without decreasing the other components of Z. Both of these mean that there is density.

According to *Definition 2,* a DMU exhibits congestion when an increase in input(s) causes a decrease in output(s). Therefore, the existence of congestion causes two main problems in DMU: one is increasing costs and the other is reducing production. Because on the one hand, congestion always reduces output and on the other hand, congestion itself is input and therefore is a cost. In this way, identifying and eliminating congestion can be useful for managing each DMU without making any changes to the production process. Hence, identifying and eliminating congestion is much more important than identifying technical inefficiencies.

Theorem 4. The second stage of $DMU_o = (X_o, Z_o, Y_o)$ exhibits congestion when at least one of the following conditions is met for the optimal solution of *Model (6),* i.e., $(\varphi^*, \lambda^*, D^{-*}, S^{+*})$:

I. $\sum_{t=1}^{p} d_t^{-*} > 0$ and $\varphi^* > 1$.

II. $\sum_{t=1}^{p} d_t^{-*} > 0$ and $\sum_{r=1}^{s} s_r^{+*} > 0$.

Proof: Assume that at least one of Cases 1 or 2 holds. Then, according to the constraints of *Model (6),* the *Relation (9)* holds:

$$\begin{aligned}
&\sum_{j=1}^{n}\mu_j^* z_{tj} = z_{to} - d_{2,t}^{-*} \le z_{to}, \quad t=1,\dots,p,\\
&\sum_{j=1}^{n}\mu_j^* y_{rj} = \varphi_2^* y_{ro} + s_{2,r}^{+*} \gneqq y_{ro}, \quad r=1,\dots,s,\\
&\sum_{j=1}^{n}\mu_j^* = 1,\ \mu_j^* \ge 0, \quad j=1,\dots,n.
\end{aligned} \tag{9}$$

The *Relation (9)* and the convexity principle resulted in $(\sum_{j=1}^{n}\mu_j^* Z_j, \sum_{j=1}^{n}\mu_j^* Y_j)$ is a member of *PPS (1)* corresponding to the second stages (Z_j, Y_j)s ($j = 1,...,n$), which can produce an output greater than Y_o (at least in one component) without worsening the input Z_o. This means that the second stage of DMU_o, i.e., (Z_o, Y_o), exhibits congestion compared to the second stages of other systems.

In this way, the amount of congestion in pth intermediate production can be achieved by the value of d_t^{-*} obtained from *Model (6)*. Similar to *Theorem 3*, if the first case of *Theorem 4* is established then decreasing the components of Z (in the role of input of Stage 2) will increase all components of output Y; and, if Case 2 holds, it means that a decrease in components of input Z causes an increase in at least one components of output Y without decreasing the other components of Z.

Theorem 5. $DMU_o = (X_o, Z_o, Y_o)$ exhibits congestion when at least one of the following conditions is met for the optimal solution of *Model (7)*, i.e., $(\varphi^*, \lambda^*, \tilde{Z}^*, S^{-*}, S^{+*})$:

I. $\sum_{i=1}^{m} s_i^{-*} > 0$ and $\varphi^* > 1$.

II. $\sum_{i=1}^{m} s_i^{-*} > 0$ and $\sum_{r=1}^{s} s_r^{+*} > 0$.

Proof: suppose that Case 1 or 2 holds. Therefore, the constraints of *Model (7)* lead to the *Relation (10)*:

$$\begin{aligned} &\sum_{j=1}^{n}\gamma_j^* x_{ij} = x_{io} - s_i^{-C*} \leq x_{io}, \quad i = 1,...,m, \\ &\sum_{j=1}^{n}\gamma_j^* y_{rj} = \varphi^* y_{ro} + s_r^{+*} \gneqq y_{ro}, \quad r = 1,...,s, \\ &\sum_{j=1}^{n}\gamma_j^* = 1, \quad \gamma_j^* \geq 0, \quad j = 1,...,n. \end{aligned} \tag{10}$$

The *Relation (10)* and the convexity principle show that $(\sum_{j=1}^{n}\gamma_j^* X_j, \sum_{j=1}^{n}\gamma_j^* Y_j)$ is a member of *PPS (1)* corresponding to the whole systems (X_j, Y_j)s ($j = 1,...,n$) which can produce an output greater than Y_o (at least in one component) without worsening the input X_o. This means that $DMU_o = (X_o, Y_o)$ exhibits congestion compared to the other systems.

In this case, the amount of congestion in ith input can be achieved by the value of s_i^{-*} obtained from *Model (7)*. Note that the establishment of Case 1 in *Theorem 5* implies that decreasing the components of primary input X will increase all components of final output Y; and, if Case 2 holds, it means that a decrease in components of input X causes an increase in at least one components of output Y without decreasing the other components of Y. This means that the whole system exhibits congestion.

So far, there is no particular objection related to *Theorems 3* to *5* and it is possible to identify and evaluate the congestion in each of the first and second stages along with the congestion in the whole system by solving the triple *Models (5)*, *(6)* and *(7)*. But the noteworthy point is the neglect of the relationship between the congestion of the stages and the congestion of the whole system. In other words, it is possible to exhibit congestion in a stage (or even both stages) according to *Models (5)* and *(6)*, while the same unit has no congestion according to *Model (7)*. Accordingly, in the next section, *Model (7)* will be modified to identify the congestion in the whole system without facing the mentioned problem.

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3 | Detection and Evaluation of Congestion in Series Two-Stage Network Structure

In this section, by developing *Model (4)* proposed by Cooper et al [1], the congestion in DMUs with a series two-stage network structures is investigated. In fact, since congestion always reduces the final output and elimination of congestion leads to an increase in the final output, congestion in a two-stage structure should also be defined according to the single-stage structure. Now, it should be noted that the final output (Y) is a function of the primary input vector (X) and the intermediate output vector (Z) in the two-stage structure. In other words, changes in the primary input as well as changes in the intermediate output can affect the final output. Therefore, an excessive increase in one of these two factors can cause congestion and therefore reduce the final output. Accordingly, the primary input vector (X) and the intermediate output vector (Z) are the factors that should be considered in defining the congestion in the two-stage structure.

Definition 5. A DMU with the series two-stage network structure exhibits overall congestion when at least one of the following conditions is met:

Case 1: A decrease (increase) in one/more components of the primary input X leads to an increase (decrease) in one/more components of the final output Y; of course, without worsening (improving) other input and output components and assuming that the intermediate production Z remains constant.

Case 2: A decrease (increase) in one/more components of the middle input Z from the second stage leads to an increase (decrease) in one/more final output components of Y; of course, without worsening (improving) other input and output components and assuming that the primary input X does not worsen.

Definition 6. The first stage of a DMU with the series two-stage network structure exhibits congestion whenever decreasing (increasing) in one/more components of primary input X leads to increasing (decreasing) in one/more final output components Y.

Definition 7. The second stage of a DMU with the series two-stage network structure exhibits congestion whenever a decrease (increase) in one/more components of the intermediate input Z from the second stage leads to an increase (decrease) in one/more components of the final output Y.

Now, according to *Definitions 5*, *6*, and *7*, the single linear programming model is proposed that considers the relationship between the stages and the whole unit and provides a logical relationship between the stages' congestion and overall congestion. This model is as *Model (11)* (where ε is a small positive non-Archimedean value):

$$\begin{aligned}
\text{Max} \quad & \varphi+\varepsilon\left(\sum_{r=1}^{s} s_r^{+}-\varepsilon\sum_{i=1}^{m} s_i^{-}-\varepsilon^2\sum_{t=1}^{p} d_t^{-}\right),\\
\text{s.t.} \quad & \sum_{j=1}^{n}\lambda_j x_{ij}+s_i^{-}=x_{io}, \quad i=1,\dots,m,\\
& \sum_{j=1}^{n}\lambda_j z_{tj}\geq z_{to}, \quad t=1,\dots,p,\\
& \sum_{j=1}^{n}\mu_j z_{tj}+d_t^{-}=z_{to}, \quad t=1,\dots,p,\\
& \sum_{j=1}^{n}\lambda_j=1, \sum_{j=1}^{n}\mu_j=1,
\end{aligned} \qquad (11)$$

$$\lambda_j \geq 0, \mu_j \geq 0, \qquad j = 1,...,n,$$
$$s_i^-, s_r^+, d_t^- \geq 0, \qquad i = 1,...,m, t = 1,...,p, r = 1,...,s.$$

It should be noted that although *Model (11)* is presented in the form of a single linear model, it requires four steps of optimization. These steps include maximizing the variable φ and then the variables $s_r^+ (r = 1,...,s)$, respectively; next, the variables $s_i^- (i = 1,...,m)$ and then $d_t^- (t = 1,...,p)$ should be minimized, respectively. Now, according to *Definition 5* to *7*, *Theorem 6* is presented to identify and evaluate the congestion in the series two-stage network structure.

Theorem 6. $DMU_o = (X_o, Z_o, Y_o)$ exhibits overall congestion if for the optimal solution of *Model (11)*, i.e., $(\varphi^*, \lambda^*, \mu^*, S^{-*}, D^{-*}, S^{+*})$, at least one of the following conditions holds:

I. $\sum_{i=1}^m s_i^{-*} + \sum_{t=1}^p d_t^{-*} > 0$ and $\varphi^* > 1$.

II. $\sum_{i=1}^m s_i^{-*} + \sum_{t=1}^p d_t^{-*} > 0$ and $\sum_{r=1}^s s_r^{+*} > 0$.

The amount of congestion in the primary inputs and the intermediate inputs of the second stage can be determined by the optimal solution $s_i^{-*} (i = 1,...,m)$ and $d_t^{-*} (t = 1,...,p)$, respectively.

The first stage of $DMU_o = (X_o, Z_o, Y_o)$ exhibits congestion if at least one of the following conditions is met for an optimal solution of *Model (11)* such as $(\bar{\varphi}^*, \bar{\lambda}^*, \bar{S}^{-*}, \bar{D}^{-*}, \bar{S}^{+*})$:

I. $\sum_{i=1}^m \bar{s}_i^{-*} > 0$ and $\varphi^* > 1$.

II. $\sum_{i=1}^m \bar{s}_i^{-*} > 0$ and $\sum_{r=1}^s \bar{s}_r^{+*} > 0$.

The values of $\bar{s}_i^{-*}$ s $(i = 1,...,m)$ indicate the amount of congestion in primary inputs.

The second stage of $DMU_o = (X_o, Z_o, Y_o)$ exhibits congestion if at least one of the following conditions is met for an optimal solution of *Model (11)* such as $(\bar{\bar{\varphi}}^*, \bar{\bar{\lambda}}^*, \bar{\bar{S}}^{-*}, \bar{\bar{D}}^{-*}, \bar{\bar{S}}^{+*})$:

I. $\sum_{t=1}^p \bar{\bar{d}}_t^{-*} > 0$ and $\bar{\bar{\varphi}}^* > 1$.

II. $\sum_{t=1}^p \bar{\bar{d}}_t^{-*} > 0$ and $\sum_{r=1}^s \bar{\bar{s}}_r^{+*} > 0$.

The values of $\bar{\bar{d}}_t^{-*}$ s $(t = 1,...,p)$ indicate the amount of congestion in intermediate inputs of the second stage.

Proof (Case (a)): Suppose that *Model (11)* achieves an optimal solution such that $\sum_{i=1}^m s_i^{-*} + \sum_{t=1}^p d_t^{-*} > 0$ and meets at least one of the conditions $\varphi^* > 1$ or $\sum_{r=1}^s s_r^{+*} > 0$. In this case, two situations may occur:

Situation 1: $\sum_{t=1}^{p} d_t^{-*} > 0$. In this case, according to the constraints of *Model (11)*, the *Relation (12)* holds for the optimal solution $(\varphi^*, \lambda^*, \mu^*, S^{-*}, D^{-*}, S^{+*})$:

$$\sum_{j=1}^{n} \lambda_j^* X_j = X_o - S^{-*}, \sum_{j=1}^{n} \lambda_j^* Z_j \geq Z_o \geq Z_o - D^{-*},$$
$$\sum_{j=1}^{n} \mu_j^* Z_j = Z_o - D^{-*} \lneqq Z_o, \sum_{j=1}^{n} \mu_j^* Y_j = \varphi^* Y_o + S^{+*} \gneqq Y_o, \quad (12)$$
$$\sum_{j=1}^{n} \lambda_j^* = 1, \sum_{j=1}^{n} \mu_j^* = 1, \lambda_j^* \geq 0, \mu_j^* \geq 0 \ j = 1,...,n,$$
$$S^{+*}, S^{-*} \geq 0, D^{-*} \gneqq 0.$$

From the *Relation (12)* it can be seen that $(X_o - S^{-*}, Z_o - D^{-*}, \varphi^* Y_o + S^{+*})$ is a member of the *PPS (3)* that can produce an output greater than the final output Y_o (at least in one input component) along with the intermediate output less than Z_o (at least in one component), without worsening the primary input X_o. This means that $DMU_o = (X_o, Z_o, Y_o)$ exhibits congestion according to Case 2 of *Definition 5*.

Situation 2: $\sum_{i=1}^{m} s_i^{-*} > 0, \sum_{t=1}^{p} d_t^{-*} = 0$. In this case, similar to Case 1, according to the constraints of *Model (11)* in the optimal solution, *Relation (13)* is obtained:

$$\sum_{j=1}^{n} \lambda_j^* X_j = X_o - S^{-*} \lneqq X_o, \sum_{j=1}^{n} \lambda_j^* Z_j \geq Z_o,$$
$$\sum_{j=1}^{n} \mu_j^* Z_j = Z_o, \sum_{j=1}^{n} \mu_j^* Y_j = \varphi^* Y_o + S^{+*} \gneqq Y_o, \quad (13)$$
$$\sum_{j=1}^{n} \lambda_j^* = 1, \sum_{j=1}^{n} \mu_j^* = 1, \lambda_j^* \geq 0, \mu_j^* \geq 0 \ j = 1,...,n,$$
$$S^{+*} \gneqq 0, S^{-*} \geq 0.$$

and from the *Relation (13)* it is concluded that $(X_o - S^{-*}, Z_o, \varphi^* Y_o + S^{+*})$ is a member of the *PPS (3)* that using a primary input less than X_o (at least in one input component) along with the intermediate output Z_o leads to the production of the final output greater than Y_o (at least in one input component). This means that $DMU_o = (X_o, Z_o, Y_o)$ exhibits congestion according to Case 1 of *Definition 5*.

Conversely, suppose that $DMU_o = (X_o, Z_o, Y_o)$ exhibits congestion according to *Definition 5*. So two cases can happen:

Case 1: Assume that Case 2 of *Definition 5* holds. Then a unit such as $(\bar{X}, Z_o, \bar{Y})$ is available in the *PPS (3)* such that $\bar{X} \lneqq X_o, \bar{Y} \gneqq Y_o$. In this case, according to the membership condition of $(\bar{X}, Z_o, \bar{Y})$ in the *PPS (3)*, there are $\bar{\lambda}_j, \bar{\mu}_j \ (j = 1,...,n)$ which satisfy the *Relations (14)*:

$$\sum_{j=1}^{n}\bar{\lambda}_j X_j = \bar{X} \lneqq X_o,$$

$$\sum_{j=1}^{n}\bar{\lambda}_j Z_j \geq Z_o,$$

$$\sum_{j=1}^{n}\bar{\mu}_j Z_j = Z_o, \tag{14}$$

$$\sum_{j=1}^{n}\bar{\mu}_j Y_j \geq \bar{Y} \gneqq Y_o,$$

$$\sum_{j=1}^{n}\bar{\lambda}_j = 1, \sum_{j=1}^{n}\bar{\mu}_j = 1, \bar{\lambda}_j \geq 0, \bar{\mu}_j \geq 0\; j = 1,\dots,n.$$

By defining the slack variables $\bar{s}_i^-(i=1,\dots,m)$, $\bar{D}^-$ and $\bar{s}_r^+(r=1,\dots s)$ in the first, third, and fourth constraints of the *Relations (14)*, respectively, this relation can be rewritten as follows:

$$\sum_{j=1}^{n}\bar{\lambda}_j x_{ij} + \bar{s}_i^- = x_{io},\; i=1,\dots,m,$$

$$\sum_{j=1}^{n}\bar{\mu}_j Z_j - \bar{D}^- = Z_o,\; (\bar{D}^- = 0) \tag{15}$$

$$\sum_{j=1}^{n}\bar{\mu}_j Y_j - \bar{s}_r^+ = \bar{\varphi} y_{ro}, r=1,\dots,s.$$

Therefore, it is concluded that $(\bar{\lambda},\bar{\mu},\bar{\varphi} \geq 1, \bar{S}^- \gneqq 0, \bar{S}^+ \geq 0, \bar{D}^- = 0)$ is a feasible solution for the *Model (11)* such that $\sum_{i=1}^{m} s_i^{-*} + \sum_{t=1}^{p} d_t^{-*} > 0$ and at least one condition $\bar{\varphi} \gneqq 1$ or $\bar{S}^+ \gneqq 0$ is established.

Case 2: Assume that Case 2 of *Definition 5* holds. In this case, a unit such as $(\bar{X},\bar{Z},\bar{Y})$ is available in the production *Possibility (3)* such that $\bar{X} \lneqq X_o, \bar{Z} \lneqq Z_o, \bar{Y} \gneqq Y_o$. In this case, the proof is similar to the previous case and we are done.

Proof: Suppose that *Model (11)* achieves the optimal solution that satisfies $\sum_{i=1}^{m} s_i^{-*} > 0$ along with at least one of the conditions $\varphi^* > 1$ or $\sum_{r=1}^{s} s_r^{+*} > 0$. In this case, according to the constraints of *Model (11)* in the optimal solution, *Relation (16)* is obtained:

$$\sum_{j=1}^{n}\lambda_j^* X_j = X_o - S^{-*} \lneqq X_o, \sum_{j=1}^{n}\lambda_j^* Z_j \geq Z_o \geq Z_o - D^{-*},$$

$$\sum_{j=1}^{n}\mu_j^* Z_j = Z_o - D^{-*}, \sum_{j=1}^{n}\mu_j^* Y_j = \varphi^* Y_o + S^{+*} \gneqq Y_o, \tag{16}$$

$$\sum_{j=1}^{n}\lambda_j^* = 1, \sum_{j=1}^{n}\mu_j^* = 1, \lambda_j^* \geq 0, \mu_j^* \geq 0,\; j=1,\dots,n,$$

$$S^{+*} \gneqq 0, S^{-*} \geq 0, D^{-*} \geq 0.$$

Now, from *Relation (16)* it follows that $(X_o - S^{-*}, Z_o - D^{-*}, \varphi^* Y_o + S^{+*})$ is a member of the production possibilities *Set (3)* with a primary input less than X_o (at least in one input component), which leads to producing a final output greater than Y_o (at least in one input component). This means that the first stage exhibits congestion according to *Definition 6*.

Conversely, suppose the first stage of $DMU_o=(X_o,Z_o,Y_o)$ exhibits congestion. Then, there is a unit like $(\bar{X},\bar{Z},\bar{Y})$ in the *PPS (3)* such that $\bar{X}\lneqq X_o,\bar{Y}\gneqq Y_o$. In this case, according to the membership condition of the *PPS (3)*, there are $\bar{\lambda}_j,\bar{\mu}_j$ which satisfy the *Relations (17)*:

$$
\begin{aligned}
&\sum_{j=1}^{n}\bar{\lambda}_j X_j=\bar{X}-S^-\lneqq X_o,\ S^-\geq 0,\\
&\sum_{j=1}^{n}\bar{\lambda}_j Z_j\geq \bar{Z},\quad \sum_{j=1}^{n}\bar{\mu}_j Z_j=\bar{Z},\\
&\sum_{j=1}^{n}\bar{\mu}_j Y_j\geq \bar{Y}\gneqq Y_o,\rightarrow(\sum_{j=1}^{n}\bar{\mu}_j Y_j+\bar{S}^+=\bar{\varphi}Y_o),\ \ (\bar{\varphi}>1\,\text{or}\,\bar{S}^+\gneqq 0),\\
&\sum_{j=1}^{n}\bar{\lambda}_j=1,\sum_{j=1}^{n}\bar{\mu}_j=1,\bar{\lambda}_j\geq 0,\bar{\mu}_j\geq 0,j=1,\dots,n.
\end{aligned}
\tag{17}
$$

From the *Relation (17)* it is concluded that a feasible solution can be found for *Model (11)* that satisfies $\sum_{i=1}^{m}\bar{s}_i^{-*}>0$ and at least one of the conditions $\bar{\varphi}^*>1$ or $\sum_{r=1}^{s}\bar{s}_r^{+*}>0$.

Remark 2: For each feasible solution of *Model (11)*, according to the constraints $\sum_{j=1}^{n}\lambda_j z_{tj}\geq z_{to}$, $\sum_{j=1}^{n}\mu_j z_{tj}+d_t^-=z_{to}$ and $d_t^-\geq 0$ it turns out that $\sum_{j=1}^{n}\lambda_j z_{tj}\geq\sum_{j=1}^{n}\mu_j z_{tj}$.

Remark 3: According to *Theorem 6*, it is clear that finding the congestion in the first and second stages is not enough to find an optimal solution for *Model (11)*. Rather, to ensure that the mentioned conditions in Cases 2 and 3 of *Theorem 6* are met, it is better to investigate the multiple optimal solutions of *Model (11)*.

Remark 4: According to the sequence of optimization steps in *Model (11)*, it is clear that the detection and evaluation of input congestion in the first stage has a higher priority than the second stage. The reason can be seen in the sensitivity of the primary input and final output components. In fact, detection and evaluation of congestion are not pleasant for decision-makers without allowing improvement in the primary input and final output.

4 | Numerical Example and Case Study

In this section, first, with a numerical example, the distinguishing power of the proposed model is compared with conventional congestion-detecting models in the series two-stage network structure. Then, the proposed model is applied to a case study.

4.1 | Numerical Example

Consider 4 DMUs with the series two-stage network structure according to *Fig. 3* with a single primary input x, single intermediate output z, and single final output y.

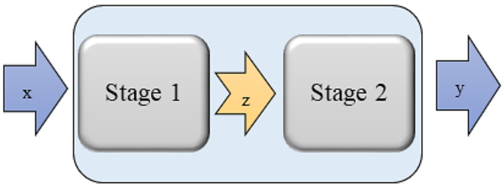

Fig. 3. A DMU with the series two-stage structure.

The related data for these 4 DMUs are listed in *Table 1*.

Table 1. Data of 4 DMUs with the series two-stage network structure.

	DMU_1	DMU_2	DMU_3	DMU_4
X	1	2	3	5
Z	0.5	2	2	1
Y	2	3	2	3

The results of *Models (5)* and *(6)* indicate the presence of congestion in the first stage of DMU_4, while this DMU does not show overall congestion according to *Model (7)*. However, according to *Model (11)*, the same DMU, in addition to the first stage, shows overall congestion too.

4.2 | Case Study

In this section, the existence of congestion in 24 Taiwanese insurance companies will be examined that are active in the non-life insurance industry [43]. As you know, the non-life insurance industry, like other service industries, expects to make a profit in exchange for providing services to its customers. But the remarkable point is that the profit of these companies is not only obtained through insurance services. Non-life insurance companies use premiums derived from systems like agencies, brokers, and lawyers as capital to support investment. With this account, the entire production process of the non-life insurance industry can be divided into two stages: 1) the premium business, and 2) the profit generation. In other words, in the first stage, each insurance company is attracted through customer insurance marketing to pay direct written premiums and premiums are also received from the other insurance companies. Then, in the second stage, the collected premiums are placed in a portfolio to make a profit.

The structure of each insurance company is shown in *Fig. 4*. The inputs of each company, which are the inputs of the first section, are the operating and insurance expenses. The operating expenses include the salaries of employees and various types of expenses incurred in daily work. On the other hand, the insurance expenses consist of expenses paid to agencies, brokers, lawyers, and other expenses associated with marketing insurance services.

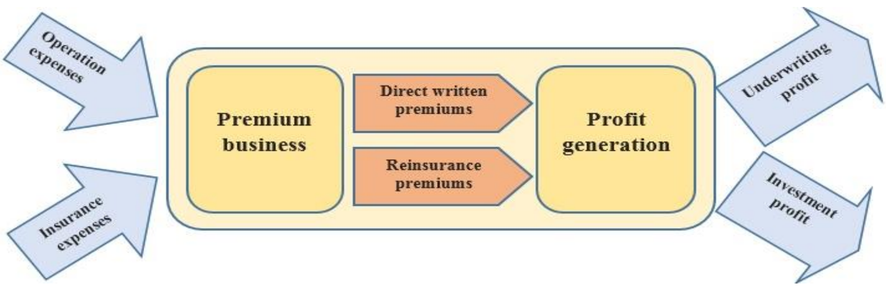

Fig. 4. Structure of the non-life insurance companies.

The outputs of each company, which is the output of the second stage, are the underwriting profit from the insurance trade and the investment profit from the investment portfolio. Also, two intermediate products correspond to each company as the output of the marketing process as well as the input of the investment process. They are the direct written premium received from the insured customers and the reinsurance premium, which is the premium received from the divested companies. *Table 2* shows the data related to each company. The results of the congestion investigation using the proposed *Model (11)* along with the results obtained from the one-model method of Cooper et al. [1] are listed in *Table 3*. The second and third columns show the results of overall congestion according to the method proposed by Cooper et al. [1], and columns 4 to 7 show the results of overall congestion according to the proposed *Model (11)*.

Table 2. Data of 24 non-life insurance companies in Taiwan.

	Operation Expenses	Insurance Expenses	Direct Written Premiums	Reinsurance Premiums	Underwriting Profit	Investment Profit
1	1178744	673512	7451757	856735	984143	681687
2	1381822	1352755	10020274	1812894	1228502	834754
3	1177494	592790	4776548	560244	293613	658428
4	601320	594259	3174851	371863	248709	177331
5	6699063	3531614	37392862	1753794	7851229	3925272
6	2627707	668363	9747908	952326	1713598	415058
7	1942833	1443100	10685457	643412	2239593	439039
8	3789001	1873530	17267266	1134600	3899530	622868
9	1567746	950432	11473162	546337	1043778	264098
10	1303249	1298470	8210389	504528	1697941	554806
11	1962448	672414	7222378	643178	1486014	18259
12	2592790	650952	9434406	1118489	1574191	909295
13	2609941	1368802	13921464	811343	3609236	223047
14	1396002	988888	7396396	465509	1401200	332283
15	2184944	651063	10422297	749893	3355197	555482
16	1211716	415071	5606013	402881	854054	197947
17	1453797	1085019	7695461	342489	3144484	371984
18	757515	547997	3631484	995620	692731	163927
19	159422	182338	1141950	483291	519121	46857
20	145442	53518	316829	131920	355624	26537
21	84171	26224	225888	40542	51950	6491
22	15993	10502	52063	14574	82141	4181
23	54693	28408	245910	49864	0.1	18980
24	163297	235094	476419	644816	142370	16976

Note that, as shown in *Table 3*, most of the companies which exhibit congestion (without considering intermediate outputs) according to the one-model method of Cooper et al. [1], exhibit congestion concerning the proposed *Model (11)*, too. Nonetheless, Companies 12 and 17 which exhibit no congestion according to Cooper et al. [1] method, exhibit congestion concerning the proposed *Model (11)*. In other words, according to the proposed model, the congestion value of company 12 in the first primary input is equal to 408221.85, and the congestion value of company 17 in the second primary input is equal to 196734.31. It should also be noted that according to the results of *Table 3*, none of the insurance companies in the second stage doesn't exhibit any congestion.

5 | Conclusion

Many real-world problems can be modeled based on the series two-stage network structure. On the other hand, congestion is one of the basic concepts in data envelopment analysis which can play an important role in reducing costs and increasing output. In this paper, it is shown that the existing classical models (especially, the one-model method of Cooper et al. [1]) are only able to detect the congestion in each stage or the whole unit independently. While ignoring the relationship between stages and the whole unit can interfere with the relationship between the congestion of stages and the congestion of the whole unit. Therefore, the definition of congestion is developed for DMUs with the series two-stage network structure. According to this definition, congestion is evaluated by providing a logical relationship between the congestion of stages and whole the system.

It should be noted that the proposed method in this study, like the model proposed by Cooper et al. [1], has a relatively long computational process. Because in 3 steps and by solving the linear programming problem 3 times, it identifies the congestion of the inputs. Anyway, since no modeling has been done to identify the congestion in the two-stage network system, this issue can be considered the innovation of the current study. On the other hand, the simplicity of interpreting the congestion calculation process can be considered another advantage of the proposed method.

Finally, the following topics can be suggested for future research:

I. Provide a method to identify the congestion in the two-stage network structure by solving a maximum of two problems (to reduce the computation complexity).
II. Development of the proposed method for more complex network structures like multi-stage structures or cases that also have initial input for the second stage.
III. Congestion detection in network structures that have an undesirable final output.

Table 3. Data of 24 non-life insurance companies in Taiwan.

	The Results of Cooper et al. Model [1]		**The Results of the Proposed Model [2]**			
	Operation Expenses	**Insurance Expenses**	**Operation Expenses**	**Insurance Expenses**	**Direct written Premiums**	**Reinsurance Premiums**
1	-	-	-	-	-	-
2	-	-	0	435381.42	0	0
3	-	-	-	-	-	
4	0	8533.51	0	170911.69	0	0
5	-	-	-	-	-	-
6	289135.71	0	415652.12	0	0	0
7	0	129975.69	0	303989.77	0	0
8	-	-	-	-	-	-
9	-	-	-	-	-	-
10	0	490690.75	0	492293.55	0	0
11	-	-	-	-	-	-
12	-	-	408221.85	0	0	0
13	-	-	-	-	-	-
14	0	64039.83	0	132124.46	0	0
15	-	-	-	-	-	-
16	-	-	-	-	-	-
17	-	-	0	196734.31	0	0
18	0	19392.62	0	39461.59	0	0
19	-	-	-	-	-	-
20	-	-	-	-	-	-
21	13109.6	0	4921.85	0	0	0
22	-	-	-	-	-	-
23	-	-	-	-	-	-
24	0	68094.56	0	50642.59	0	0

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Designing a Hybrid Model for the Green Supply Chain in Guilan Steel Industry

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Abstract

Due to the importance of environmental effects of manufacturing system in recent decades, the production systems are obliged to comply different environmental regulations. The present research, aims to design a green supply chain model for Guilan Steel industry with a hybrid approach. This study is applied research in term of purpose, exploratory in term of method, quantitative and qualitative in terms of data type. A researcher made questionnaire are applied, in addition to interview, for data gathering. The under-study research population includes steel industry experts out of them, 12 experts were selected for data gathering phase. Conducting the research, first applying fuzzy Delphi method, 5 main factors and 25 important sub-factors were identified. Then, using fuzzy DEMATEL and Interpretive Structural Modeling (ISM) methods, the importance of each facto was determined, in which two factors "external environment study" and "internal environment study" were at the highest level of the importance, while "waste reduction", "waste recycling" and "purchasing based on environmental products" were at the last level. These variables are interrelated and affect their next levels.

Keywords: Green supply chain, Delphi method, Fuzzy DEMATEL, ISM.

1 | Introduction

Supply chain of the organizations can be simply defined as a set of directly involved entities in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer [1]. Today, competition along or across chains is of particular importance among researchers. The supply of products and services by changing the pattern of customer competition has led to a change in the type of market competition from the state of competition between independent companies to competition between supply chains. Supply chain design has extensive literature, most of which is related to the single supply chain, and the existence of competing supply chains and their emergence in the future have not been considered. However, supply chains compete with each other for greater market share. Therefore, supply chains must be prepared for future competitiveness even if there is no competitor at the same time [2].

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In recent years, the advent of new technologies and shifts in global markets have necessitated the Supply Chain Management (SCM), so that different organizations use SCM inevitably to create and maintain their competitive position [3]. SCM involves the planning of the entire supply chain from the raw material supplier to the end customer. Since SCM has become the core of the organization's management in the 21st century, there is a high interest to exploit the full potential of SCM in increasing organizational competitiveness [4]. SCM is considered as a business strategy. It has evolved over time from a focus on optimizing the internal processes of an organization [1].

Green Manufacturing (GM) is introduced as a manufacturing process that utilizes input data with relatively low environmental impacts, whereas is highly efficient and creates little waste or pollution, and Greenhouse Gas Emission (GHG) [5]. Today's world experiences an increase in pollution, environmental problems and countries' concerns about the earth climate. Climate change is quite obvious at present, and its impact is falling adversely on the population and the world economy [6]. It caused to increase in environmental concerns from consumers, manufacturing companies, governments and communities around the world. On the other hand, global organizations attemp to cerate competitive advantage by improving their environmental performance according to the environmental laws and standards and increasing customers' knowledge about green products and services. Therefore, the necessity of green supply chains has obliged governments to set environmental standards and on the other hand the demand of customers for the supply of green products [7]. It has been more than two decades since green SCM has been studied. Many companies and industries are keen to initiate a partnership with the suppliers, so they would be able to enhance their competitiveness performance globally [8].

The functions of green supply chain are summarized in three important themes: green design (product), green production (process), and product recycling. In fact, the green supply chain is based on the integration of internal and external measures to control environmental effects on the product life cycle by sharing information, coordination and cooperation of the all players in supply chain [9]. Green SCM integrates SCM with environmental requirements at all stages. Internal and external actions in the supply chain include product design, selection and supply of raw materials, production and manufacturing, distribution and transfer processes, delivery to the customer and, recycling in order to maximize energy efficiency. Since the issue of the environment was linked to the economy and countries have come to the conclusion that environmental protection can increase productivity, different approaches have been taken to realize these technologies, one of which is the latest, the green SCM [10]. The idea of green SCM is to eliminate or minimize waste, which as an important innovation helps the organization to develop strategies to achieve common profit and market goals by reducing environmental risks and enhancing environmental efficiency [11]. Homayounfar et al. [12] proposed a hybrid fuzzy MCDM approach based on fuzzy Delphi, fuzzy analytical hierarchy process and fuzzy VIKOR techniques to evaluate and select the green suppliers of Saipa Corporation. The results indicate that the proposed approach is an effective framework for prioritizing green suppliers of Saipa Corporation. Examining the theoretical issues of the research shows that companies are increasingly believing that considering green SCM measures and observing them as a key strategy could lead to great impact on organizational performance. Rezaee Kelidbari et al. [13] used a combined multiple criteria decision-making method (extent analysis and PROMETHEE) for supplier selection in a spare producer company in Iran. The result of this belief can be seen in the implementation of ISO 14001 standard by most companies. For example, Laari et al. [14] stated that paying attention to green management activities will improve the performance of the organizations in financial and environmental dimensions. Therefore, identifying green SCM measures can be very important. Some researchers believe that waste reduction, total quality management, ISO standards and reverse logistics, which are measures of green SCM, have a significant effect on green productivity. Thus, it can be said that in today's era, various organizations and industries by identifying and observing green SCM measures such as waste reduction, total quality management, green production, green design, reverse logistics, etc. can easily achieve the goals with more efficiency [15]. However, the industrial development trend shows that, the green issues are neglected by many

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industries especially in developing countries. So, this study aims to present a hybrid model to investigate the green supply chain in Guilan Steel industry as one of the leading industries in Iran.

2 | Methodology

This research is descriptive-survey in terms of method and practical in terms of purpose. In term of time horizon, it is cross-sectional research and from the methodological point of view, this research is based on mix methodology. The experts include academic experts in supply chain and top managers of Guilan Steel company who are familiar with SCM which have the following conditions: 1) at least 10 years of work experience, 2) at least 5 years of work experience in managerial positions, 3) having a master's degree or higher in the fields of industrial management or industrial engineering. According to the mentioned features, 5 academic experts and 7 industry experts were identified as research experts to conduct the research, based on the literature review and studying the scientific papers related to the green supply chain, its criteria were extracted. In this research, first a Delphi questionnaire was designed based on the factors identified from the literature review and was sent to the experts in 3 rounds. Analyzing the answers using, 25 more important factors of green supply chain with the score of ≥ 0.7 were selected. Finally, in order to investigate the relationships between the main factors, other questionnaires were designed and sent to the research experts. According to the answers and applying Interpretive Structural Modeling (ISM) and DEMATEL methods these factors were structured and the critical ones were identified. The software used to implement the data analysis was, MATLAB software. In the following, methods used for data analysis are described.

2.1 | Fuzzy Delphi

Fuzzy Delphi method introduced by Ishikawa et al. [16] is a method derived from the traditional Delphi method and fuzzy set theory. According to Noorderhaben's study, fuzzy Delphi method solves the ambiguities in experts' opinions to a large extent [12]. In the first step of the research, fuzzy Delphi method is used to screen the factors identified in theoretical bases. In the next step, a questionnaire containing factors will be sent to the experts to determine the importance of each factor based on linguistic values (*Table 2*). After collecting the questionnaires, the results of the first round were sent to the experts in the form of a questionnaire so that they modify their judgments after reviewing the results of the initial stage, if it is needed. After collecting and analyzing the experts' judgments in the second round, the average difference was checked, if this difference is less than 0.2, consensus is achieved and the fuzzy Delphi steps will be completed. Otherwise, the analysis of the results of this round will also be sent to the experts, again. This process will continue until the experts achieve to the consensus in the judgments. If the experts decide to add a criterion during these rounds, this criterion will be added to the questionnaire in the next round and opinions about this criterion will be asked. At the end, in order to confirm the final criteria, the average score of each criterion should be compared with the threshold value (0.7). For this purpose, first the triangular fuzzy numbers of experts' judgments should be calculated and then their fuzzy average should be calculated to compute the average of n respondents' judgments. In this study, *Table 1* illustrates the utilized scale for transforming linguistic words into triangular fuzzy numbers.

Table 1. Verbal words and their fuzzy values.

Fuzzy Value	Linguistic Value
(7, 9, 9)	Very high
(5, 7, 9)	High
(3, 5, 7)	Medium
(1, 3, 5)	Low
(1, 1, 3)	Very low

2.2 | DEMATEL Method

DEMATEL is a graph theory-based technique, was first put forward by American scientist in Science and Human Affairs Program (SHAP) between 1972 and 1976 to resolve the complicated and intertwined problem group [17]. This structural modeling approach adopts the form of a directed graph, a causal-effect diagram, to present the interdependence relationships and the values of influential effect between factors. Through analysis of visual relationship of levels among system factors, all elements are divided into causal group and effected group and this can help researchers better understand the structural relationship between system elements, and find ways to solve complicate system problems [18]. At first, DEMATEL method focused primarily on the fragmented and even contradictory phenomenon to find a reasonable solution. With further research, this method has been widely applied in more and more areas. Currently, DEMATEL method has been applied to many fields. Moreover, DEMATEL method is currently applied in many other areas. The steps of DEMATEL method based on Sharifi and Homayounfar [19] are as follows:

1. Find out the factors influencing the under-examination system. A large number of literature reviews is required to search and collect relevant information in this phase.
2. Generate the initial direct-relation matrix form a committee of experts, and acquire the assessments about direct affect between each pair of elements. Converting the linguistic assessments into crisp values, we obtain the direct-relation matrix A = [aij], where A is a n×n non-negative matrix, aij indicates the direct impact of factor i on factor j. When i = j the diagonal elements are zero (aij = 0).
3. Normalize the initial direct-relation matrix (D) through *Eq. (1)*. All elements in matrix D are complying with $0 \le d_{ij} \le 1$, and all principal diagonal elements are equal to 0.

$$D = \frac{1}{\max \sum_{j=1}^{n} a_{ij}} \ . \ A. \quad (1)$$

4. Acquire the total-relation matrix T using the *Eq. (2)* in which I is a n×n identical matrix. The element tij indicates the indirect effects that factor i have on factor j, so the matrix T can reflect the total relationship between each pair of system factors.

$$T = D\,(I - D)^{-1}. \quad (2)$$

5. Calculate the sum of rows and columns in matrix T through *Eqs. (3)* and *(4)*. The sum of row i (ri) represents all direct and indirect influence given by factor i to all other factors, and so ri can be called the degree of influential impact. Similarly, the sum of column j (cj) can be called as the degree of influenced impact, since cj summarizes both direct and indirect impacts received by factor j from all other factors.

$$r_i = \sum_{j=1}^{n} t_{ij}. \quad (3)$$

$$c_j = \sum_{i=1}^{n} t_{ij}. \quad (4)$$

Naturally, when i = j, the indicator ri + ci can represent all effects received by factor i. On the contrary, ri - ci shows the net effect that factor i has on the whole system. Specifically, if the value of ri - ci is positive, the factor i is a net cause, exposing net causal effect on the system. When ri - ci is negative, the factor is a net result clustered into effect group.

6. Construct cause-effect relationship diagram based on ri + cj and ri - cj. A cause-effect diagram can be drawn by mapping the dataset of (ri + cj, ri - cj).

2.3 | ISM Method

ISM is a method by which the effect of each element of the system on other varelements can be structured and analyzed. This approach, provide a comprehensive attitude to the system and details its performance [20]. In addition to ordering and directing the relations among the items of a system, the method helps to analyze and evaluate the effect of an element on other elements. Thereby, the relational

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complexity among the items is coped with, and the elements are ultimately classified on the basis of their drivingdependence power. The various steps of ISM method as follow:

Step 1. List the elements of the system.

Step 2. Establish the relationships among the elements in form of the Structural Self-Interaction Matrix (SSIM).

Step 3. Developed the reachability matrix based on the SSIM, and the matrix is checked for transitivity. The transitivity indicates that, if variable A is related to B and B is related to C, then A is necessarily related to C.

Step 4. Structure the elements of the reachability matrix into different levels.

Step 5. Depict a hierarchial graph based on the relationships in the reachability matrix.

Step 6. Review the ISM model developed in Step 5 to check against conceptual inconsistencies, and necessary modifications are made.

3 | Results

Since, the green SCM factors derived from the literature are to many, it is rational that a screening method be applied to filter the important factors. Therfore, a questionnaire consisting 35 items was designed for evaluating based on a five-point scale from unimportant to extremely important. Then, the most important factors were determined with the fuzzy Delphi technique in three rounds. This technique was applied at the level of both factors and subfactors. Here, we present the rounds and results of the fuzzy Delphi at the subfactor level. To this end, a questionnaire was first distributed among 12 experts. *Table 2* summarizes the results.

Table 2. Results of the first round of the Delphi method.

Non-Fuzzy Average of Expert Opinions	Min	Mod	Max	Very Low 1 (0,1,3)	Low 3 (1,3,5)	Medium 5 (3,5,7)	High 7 (5,7,9)	Very High 9 (7,9,10)	Linguistic Values Numerical Values Fuzzy Value	Component
8.09	6.20	8.20	9.52	0	0	2	6	17	Suitability of material prices to market prices	Financial factors
7.86	5.96	7.96	9.46	0	0	3	7	15	Transportation cost	
8.16	6.28	8.28	9.56	0	0	2	5	18	Product price	
7.93	6.04	8.04	9.36	0	0	4	4	17	Order Cost	
8.16	6.28	8.28	9.56	0	0	2	5	18	Defective rate	
7.94	6.04	8.04	9.44	0	0	2	8	15	Management commitment to quality	Quality factor
8.24	6.36	8.36	9.64	0	0	1	6	18	Guarantees and policies	
6.08	4.12	6.12	7.88	0	4	9	6	6	Ability to achieve abnormal quality	
7.64	5.72	7.72	9.16	0	1	3	7	14	ISO quality management system	
7.94	6.04	8.04	9.44	0	0	2	8	15	Quality guarantee	
5.07	4.08	5.08	7.00	0	9	8	6	2	System of corrective and preventive measures	
4.44	2.44	4.44	6.44	0	15	2	8	0	Process improvement	
4.28	2.28	4.28	6.28	0	16	2	7	0	Timely delivery	

Table 2. Continued.

Non-Fuzzy Average of Expert Opinions	Min	Mod	Max	(0,1,3) 1 Very Low	(1,3,5) 3 Low	(3,5,7) 5 Medium	(5,7,9) 7 High	(7,9,10) 9 Very High	Linguistic Values / Numerical Values / Fuzzy Value	Component
7.94	6.04	8.04	9.44	0	0	2	8	15	Technology level	
7.63	5.72	7.72	9.16	0	0	5	6	14	Research and development capabilities	
6.63	4.68	6.68	8.40	0	2	7	9	7	Current production capabilities or facilities	
6.79	4.84	6.84	8.52	0	2	6	9	8	Development of supplier technology for…	
7.77	5.88	7.88	9.24	0	1	3	5	16	Technology compatibility	Technology factors
4.36	2.40	4.36	6.32	1	9	13	1	1	Technological capacity	
8.29	6.32	8.40	9.80	0	0	3	6	17	Ability to prevent contamination	
8.17	6.28	8.28	9.60	0	0	1	7	17	Environmental certification such as ISO 14000	
7.94	6.04	8.04	9.44	0	0	2	8	15	Environmental productivity	
4.28	2.28	4.28	6.28	0	16	2	7	0	RoHS compliant	
3.86	1.88	3.84	5.92	3	16	2	5	0	Protection program or policy…	
8.31	6.44	8.44	9.68	0	0	1	5	19	Environmental policies	
8.24	6.36	8.36	9.64	0	0	1	6	18	Continuous monitoring and compliance	Ecology factor
7.71	5.80	7.80	9.24	0	0	4	7	14	Green process planning	
8.26	6.28	8.28	9.56	0	0	2	5	18	Check the interior	
7.85	5.96	7.96	9.32	0	0	4	5	16	Examination of the external environment	
6.01	4.04	6.04	7.84	0	5	7	8	5	Environmental constraints	
3.99	2.12	3.96	5.96	4	9	8	4	0	Pay attention to uncertainty	
8.17	6.28	8.28	9.64	0	0	0	9	16	Waste reduction	
7.94	6.04	8.04	9.44	0	0	2	8	15	Recycling	Environmental factor
7.86	5.96	7.96	9.31	0	0	3	7	15	Shopping based on products…	
6.01	4.04	6.04	7.84	0	5	7	8	5	Flexibility	

In the second round, the desinged questionnaire was prepared and sent to the experts for the second time. Collecting the distributed questionnaire and measuring the differences between average responses in first and second round, the confirmed factors were determined. The results of the calculations are presented in *Table 3*.

According to the views presented in the first stage and its comparison with the results of this stage, according to the Pareto (20/80) rule, if the difference between the two stages is less than the threshold of 0.2, then the poll process will stop. As the table above shows, some of the variables, the members of the expert group have reached a consensus and the amount of disagreement in the first and second stages was less than the threshold of 0.2, so the survey on the above variables was stopped. Among the mentioned variables, the variables that have a non-fuzzy average of expert opinions less than 8 were removed from the conceptual model of the research. The poll will continue in the third stage.

Table 3. Results of the second round of Delphi method.

Result	Differences between the Means of the First and Second Questionnaires	Non-Fuzzy Average of Expert Opinions	Min	Mod	Max	Very Low	Low	Medium	High	Very High	Linguistic Value	Component
						1	3	5	7	9	Numerical Value	
						(0,1,3)	(1,3,5)	(3,5,7)	(5,7,9)	(7,9,10)	Fuzzy Value	
Confirmed	0.07	8.16	6.28	8.28	9.56	0	0	2	5	18	Suitability of material prices to Market prices	Financial factors
Confirmed	0.15	8.01	6.12	8.12	9.44	0	0	3	5	17	Transportation cost	
Confirmed	0.15	8.31	6.44	8.44	9.68	0	0	1	5	19	Product price	
Next	0.53	8.46	6.60	8.60	9.76	0	0	1	3	21	Order Cost	
Confirmed	0.07	8.23	6.36	8.36	9.60	0	0	2	4	19	Defective rate	
Confirmed	0.15	8.09	6.20	8.20	9.52	0	0	2	6	17	Management commitment to quality	
Confirmed	0.15	8.39	6.52	8.52	9.72	0	0	1	4	20	Guarantees and policies	
Unconfirmed	0.13	5.95	3.96	5.96	7.88	0	1	13	9	2	Ability to achieve abnormal quality	Quality factor
Next	0.47	8.09	6.20	8.20	9.56	0	0	1	8	16	ISO quality management system	
Confirmed	0.07	8.01	6.12	8.12	9.48	0	0	2	7	16	Quality guarantee	
Unconfirmed	0.15	4.92	2.92	4.92	6.92	0	7	12	6	0	System of corrective and preventive measures	
Unconfirmed	0.08	4.36	2.36	4.36	6.36	0	15	3	7	0	Process improvement	
Unconfirmed	0.08	4.20	2.36	4.20	6.04	0	11	6	6	0	Timely delivery	
Confirmed	0.08	8.02	6.12	8.12	9.52	0	0	1	9	15	Technology level	
Next Round	0.61	8.24	6.36	8.36	9.64	0	0	1	6	18	Research and development capabilities	
Unconfirmed	0.07	6.56	4.60	6.60	8.36	0	2	7	10	6	Current production capabilities or facilities	Technology factors
Unconfirmed	0.07	6.71	4.76	6.76	8.48	0	2	6	10	7	Development of supplier technology for ...	
Next Round	0.47	8.24	6.36	8.36	9.64	0	0	1	6	18	Technology compatibility	
Unconfirmed	0.16	4.20	2.20	4.20	6.20	0	10	15	0	0	Technological capacity	
Confirmed	0.12	8.17	6.28	8.28	9.60	0	0	1	7	17	Ability to prevent contamination	
Confirmed	0.15	8.32	6.44	8.44	9.72	0	0	0	7	18	Environmental certification such as ISO 14000	
Confirmed	0.08	8.02	6.12	8.12	9.52	0	0	1	9	15	Environmental productivity	Ecological Factor
Unconfirmed	0.08	4.20	2.20	4.20	6.20	0	15	5	5	0	RoHS compliant	
Unconfirmed	0.12	3.74	1.84	3.72	5.72	3	16	0	6	0	Protection program or policy...	
Confirmed	0.15	8.47	6.60	8.60	9.80	0	0	0	5	20	Environmental policies	

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Table 3. Continued.

Result	Differences between the Means of the First and Second Questionnaires	Non-Fuzzy Average of Expert Opinions	Min	Mod	Max	Very Low 1 (0,1,3)	Low 3 (1,3,5)	Medium 5 (3,5,7)	High 7 (5,7,9)	Very High 9 (7,9,10)	Linguistic Value / Numerical Value / Fuzzy Value	Component
Confirmed	0.15	8.39	6.52	8.52	9.72	0	0	1	4	20	Continuous monitoring and compliance	Environmental factor
Next Round	0.46	8.17	6.28	8.28	9.60	0	0	1	7	17	Green process planning	
Confirmed	0.15	8.31	6.44	8.44	9.68		0	1	5	19	Check the interior	
Confirmed	0.16	8.01	6.12	8.12	9.48	0	0	2	7	16	Examination of the external environment	
Unconfirmed	0.01	6.02	4.04	6.04	7.92	0	3	9	10	3	Environmental constraints	
Unconfirmed	0.01	3.97	2.04	3.96	5.96	2	11	10	2	0	Pay attention to uncertainty	
Confirmed	0.07	8.25	6.36	8.36	9.68	0	0	0	8	17	Waste reduction	
Confirmed	0.16	8.10	6.20	8.20	9.60	0	0	0	10	15	Recycling	
Confirmed	0.15	8.01	6.12	8.12	9.44	0	0	3	5	17	Shopping based on products...	
Unconfirmed	0.16	6.17	4.20	6.20	8.00	0	3	9	8	5	Flexibility	

Survey of the third stage

In this stage, while applying the necessary changes in the model variables, the third questionnaire was prepared and sent to the experts again with the previous point of view of each person and the extent of their differences with the average views of other experts. The difference is that at this stage, 30 of the components in the previous stage were stopped and a survey was conducted on the remaining 5 components, the results of which are presented in *Table 5*.

Table 4. Results of the second round of Delphi method.

Result	Differences Between the Means of the First and Second Questionnaires	Non-Fuzzy Average of Expert Opinions	Min	Mod	Max	Very Low 1 (0,1,3)	Low 3 (1,3,5)	Medium 5 (3,5,7)	High 7 (5,7,9)	Very High 9 (7,9,10)	Linguistic Value / Numerical Value / Fuzzy Value
Confirmed	0.07	8.39	6.52	8.52	9.76	0	0	0	6	19	Order Cost
Confirmed	0.08	8.17	6.28	8.28	9.64	0	0	0	9	16	ISO quality management system
Confirmed	0.08	8.32	6.44	8.44	9.72	0	0	0	7	18	Research and development capabilities
Next round	0.15	8.39	6.52	8.52	9.72	0	0	1	4	20	Technology compatibility
Confirmed	0.07	8.09	6.20	8.20	9.56	0	0	1	8	16	Green process planning

As the table above shows, the amount of disagreement of experts in the second and third stages is less than the threshold of 0.2, and therefore the poll is stopped at this stage. The fuzzy Delphi results showed that in order of weight of criteria, out of 35 sub-factors, 12 sub-factors were removed from the final conceptual model of the research and finally there was a consensus for 5 main indicators along with 23 effective sub-indicators. Now, to the first question of the research, "what are the indicators affecting the green supply chain in the steel industry of Guilan province?" it was answered that the most important factors are identified in *Table 5*.

Table 5. Factors and sub-factors affecting the green supply chain.

Code	Sub-Factors	Factors
C_{11}	Suitability of material prices to market prices	Financial factor
C_{12}	Transportation cost	C_1
C_{13}	Product price	
C_{14}	Order Cost	
C_{21}	Defective rate	Quality factor
C_{22}	Management commitment to quality	C_2
C_{23}	Warranties and Policy	
C_{24}	ISO quality management system	
C_{25}	Quality assurance	
C_{31}	Technology level	Technology factor
C_{32}	R&D capability	C_3
C_{33}	Technology compatibility	
C_{34}	Ability to prevent contamination	
C_{41}	Environmental certification such as ISO 14000	Ecology factor
C_{42}	Environmental productivity	C_4
C_{43}	Environmental policies	
C_{44}	Continuous monitoring and compliance with regulations	
C_{45}	Green process planning ISO 14000	
C_{51}	Examination of the interior	Environmental factor
C_{52}	Examination of the external environment	C_4
C_{53}	Reduction of waste	
C_{54}	Waste recycling	
C_{55}	Purchase based on environmental products	

Finally, according to the factors and factors listed in *Table 5*, the hierarchial model was formed as follows:

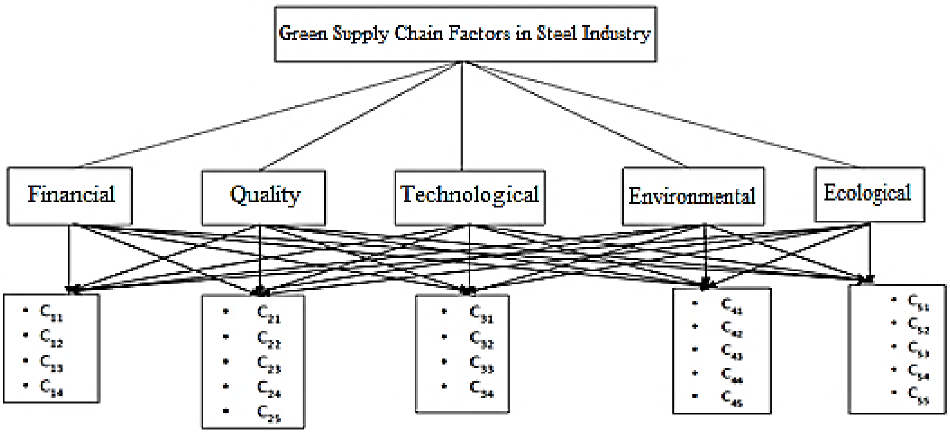

Fig. 1. Hierarchial structure of the factors.

DEMATEL solution

The sum of the elements of the columns and rows of the matrix $\tilde{T}$ are calculated for the main factors and their sub-factors and are named as vectors $\tilde{R}$ (influencing) and $\tilde{D}$ (to be oinfluenced). The calculations are mentioned in *Tables 6* and *7*.

Table 6. Criteria values $\tilde{R}$, $\tilde{D}$, $\tilde{R}$ + $\tilde{D}$, $\tilde{R}$-$\tilde{D}$.

Factors	$\tilde{D}$	R	$\tilde{D}+R$	$\tilde{D}-R$	Result
Financial	0.901	1.897	2.798	-0.996	The most effective
Quality	1.293	1.321	2.614	-0.028	Effective
Technology	1.524	0.84	2.364	0.684	Effective
Ecologicy	1.096	1.548	2.644	-0.452	Effective
Enviromental	1.651	0.858	2.509	0.792	The most effective

Table 7. Non-standard values $\tilde{R}$, $\tilde{D}$, $\tilde{R}$ + $\tilde{D}$, $\tilde{R}$-$\tilde{D}$.

Main Factors	Sub-Factors	$\tilde{D}$	R	$\tilde{D}+R$	$\tilde{D}-R$
Financial factor C_1	Suitability of material prices to Market prices	0.394	0.322	0.715	0.0717
	Transportation cost	0.392	0.355	0.747	0.0364
	Product price	0.356	0.384	0.739	-0.028
	Order Cost	0.32	0.4	0.72	-0.08
Quality factor C_2	Defective rate	0.373	0.373	0.746	0.0003
	Management commitment to quality	0.473	0.393	0.866	0.0794
	Warranties and Policy	0.355	0.346	0.701	0.0093
	ISO quality management system	0.332	0.367	0.699	-0.035
	quality assurance	0.282	0.336	0.619	-0.054
Technology factor C_3	Technology level	0.389	0.391	0.78	-0.002
	R&D capability	0.367	0.365	0.732	0.0012
	Technology compatibility	0.354	0.457	0.812	-0.103
	Ability to prevent contamination	0.364	0.351	0.714	0.0131
Ecology factor C_4	Environmental certification such as ISO 14000	0.454	0.418	0.871	0.036
	Environmental productivity	0.392	0.391	0.783	0.0004
	Environmental policies	0.444	0.432	0.876	0.0115
	Continuous monitoring and compliance with regulations	0.393	0.357	0.75	0.0367
	Green process planning ISO 14000	0.336	0.42	0.756	-0.085
Environmental factor C_4	Examination of the interior	0.355	0.312	0.667	0.0427
	Examination of the external environment	0.323	0.305	0.628	0.0179
	Reduction of waste	0.325	0.306	0.631	0.0184
	Waste recycling	0.304	0.308	0.612	-0.004
	Purchase based on environmental products	0.282	0.357	0.64	-0.075

Fig. 2 shows the importance of impact and effectiveness between criteria. The horizontal axis of the graph shows the importance of the criteria and the vertical axis shows the effectiveness of the criteria. Therefore, it can be concluded that the importance and effectiveness of the criteria are "environmental factor", "technology factor", "quality factor", "environmental factor" and "financial factor", respectively. Indicators that have a positive $\tilde{D}$-R according to *Table 4* of the value definitely show the effectiveness of these factors, and factors that have a negative $\tilde{D}$-R indicate the definite influence of these factors on other factors; Therefore, among the main factors, "environmental factor" with an impact value of 0.792 is the most effective and "financial factor" with a net impact value of -0.996 are the most effective indicators. In general, positive $\tilde{D}$-R, causal factors and negative $\tilde{D}$-R are considered effective disability factors. At this time, to the second question of the research, "what is the causal relationship (effectiveness and effectiveness) between the criteria affecting the green supply chain in the steel industry of Guilan province?" was answered. Finally, the cause-and-effect relationships are plotted by drawing points with coordinates $\tilde{D}$ + $\tilde{R}$ and $\tilde{D}$-R based on the T matrix and the degree to which factors affect

each other in a Cartesian coordinate system. Accordingly, the cause-and-effect diagram and the map of network networks of factors are shown in *Fig. 2*.

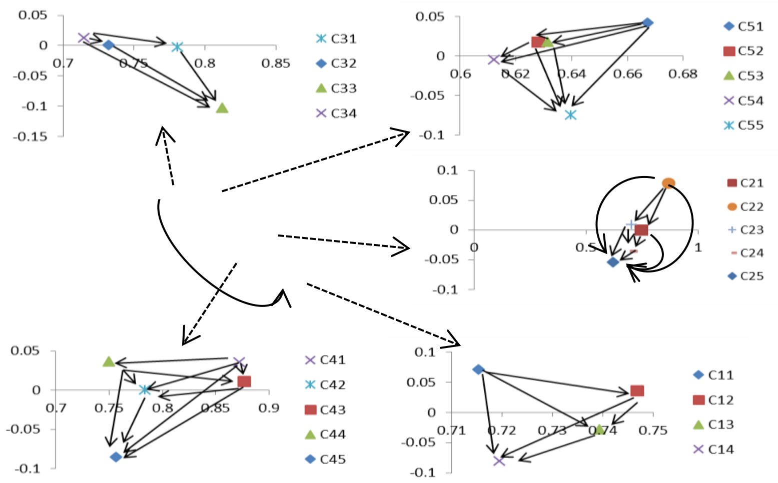

Fig. 2. Network map of the relationship between the main criteria and sub-criteria.

In this section, the structural-interpretive method is used for modeling, in which the relationship and how their effects and segregation for the green supply chain in the steel industry are determined. Problem solving in the present study with structural-interpretive method is as follows:

Table 8. Determining the levels of factors affecting the green supply chain in the steel industry.

Factors		D	R	D-R	Level	Result
Product price	4	-22	23	-22	1	dependent
Suitability of material prices to market prices	1	-18	22	-18	2	dependent
Order Cost	2	-18	22	-18	2	dependent
Transportation cost	3	-18	22	-18	2	dependent
Defective rate	8	-13	19	-13	3	dependent
Quality assurance	9	-13	19	-13	3	dependent
Environmental productivity	15	-9	17	-9	4	dependent
Green process planning ISO 14000	18	-9	17	-9	4	dependent
ISO quality management system	5	-4	15	-4	5	dependent
Management commitment to quality	7	-4	15	-4	5	dependent
Environmental certification such as ISO 14000	16	-4	15	-4	5	dependent
Warranties and Policy	6	2	12	2	6	free
Continuous monitoring and compliance with regulation	14	2	12	2	6	free
Environmental policies	17	2	12	2	6	free
Ability to prevent contamination	10	7	9	7	7	Independent
Technology compatibility	12	7	9	7	7	Independent
R& D ability	11	11	7	11	8	Independent
Technology level	13	11	7	11	8	Independent
Reduction of waste	20	16	5	16	9	Independent
Waste recycling	22	16	5	16	9	Independent
Purchase based on environmental products	23	16	5	16	9	Independent
Examination of the external environment	19	21	2	21	10	Independent
Examination of the interior	21	21	2	21	10	Independent

After determining the relationships and level of variables, they can be drawn as a model. For this purpose, we first adjust the variables in descending order according to their level. In the present study, the factors are in 10 levels. *Fig. 3* shows the model of interpretive structure to separate the effective factors of green supply chain in the steel industry.

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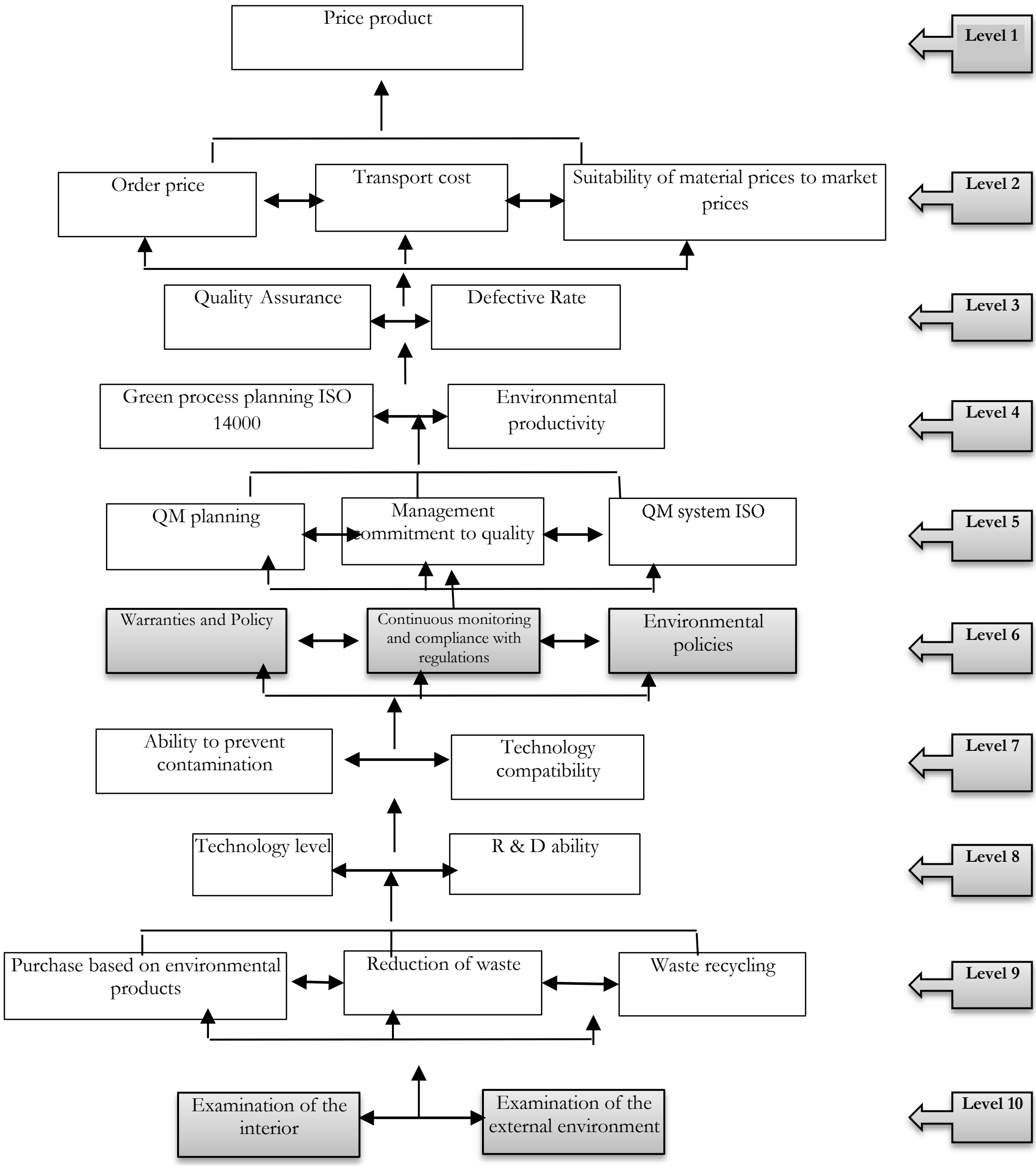

Fig. 3. Interpretive-structural model for green supply chain in steel industry.

At the highest level of the model (Level 10) there are two factors "external environment study" and "internal environment study" that act as the foundation of the model that the green supply chain in the steel industry starts from these factors and spreads to others. The factors "waste reduction", "waste recycling" and "purchasing based on environmental products" are at level 9. These variables are interrelated and affect their next levels. These factors are affected by the previous level and affect the next level factor. In the second level, there are three factors "suitability of material price to market price", "order cost" and "shipping cost", which in addition to affecting the first level, also have internal relations with each other. The second level factors affect the first level factors of "product price" which leads to the green supply chain. The "product price" factor is a component that is the result of other factors planned in the green supply chain.

4 | Conclusions

The first purpose of this study was to identify the factors affecting the green supply chain in the steel industry, especially Guilan Steel Company. According to the research conducted in the field of research and after screening, 23 important factors were identified, the main criteria of which are "financial, quality, technology, environmental and environmental" factors, which are in line with the first goal of the research.

The second purpose of the study was to determine the relationships and effects of factors on each other. To achieve this goal, the fuzzy DEMATEL technique was used. The results of this technique are described as follows: "Financial factor" is the most influential factor in the green supply chain in the steel industry. In other words, this factor is the main problem and bottleneck of improving the supply chain design in the organization, which is solved by influential factors. In fact, the success or failure of the green supply chain depends on this factor; therefore, it can be concluded that in order to achieve organizational productivity, the organization must be in the green supply chain to the financial factor and so on. Note. This finding is in line with the findings of researchers such as Malviya and Kant [15], Chand et al. [21], Govindan et al. [22], Kannan et al. [23], Wang et al. [24] and so on. "Environmental factor" is also the most influential factor in the green supply chain. In other words, it is the criterion that is most important and solves the problem and should be prioritized to improve the system. It can be concluded that environmental factors have a significant impact on the green supply chain. Also, the management factor can increase the efficiency and improve processes, etc. can be an effective factor in the green supply chain and its use in the organization. This finding is in line with the findings of Malviya and Kant [15], Tseng et al. [25], Azad [26], Yazdani et al. [27], Ansari and Sadeghi Moghaddam [28] and etc.

According to the ISM, two factors, "external environment study" and "internal environment study" are at the highest level of the model and we should try to use the intensity of this criterion to strengthen the system. Therefore, it is recommended to the senior managers of the organization and the decision-making department of the steel industry, especially steel of Guilan province (private joint stock company) by reducing the price of the product, reducing the cost of transportation, improving the cost of ordering, the appropriateness of material prices to market prices. They should try to maintain their competitive position and should try to make the company under study successful with suggestions. Because the success or failure of the company is to this criterion (the most effective) and we should try to use the intensity of penetration of this criterion to strengthen the system. Therefore, senior managers and decision-makers of the steel industry, especially steel in Guilan province (private joint stock company) are advised to try to further reduce waste and such cases to increase and maintain their competitive position by using the study of the external environment and the study of the internal environment.

The Main limitation of the research was the lack of access to experts during office hours, so an attempt was made to get experts judgments out of the work hours. The other limitation of the research is arised from the diversification of the green supply chain factors which needs to comprehensive research in such as literature review. For conducting the future studies, in recommends to researchers to study the green supply chain papers and deeply investigate its factors, drivers, obstacles, threats, and etc and teoritically contribute on this literature. Also, the qualitative modelling methods such as theme analysis, grounded theory and similar methods are recommended to use as conceptualization of this scope.

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Conflicts of Interest

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

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Identifying and Prioritizing Technology Capability Drivers in the Supply Chain Using the Fuzzy Hierarchical Analysis Process (Case Study: Iran Khodro and Saipa Automotive Company)

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Abstract

This study aims to identify and prioritize the effect of technology capability drivers on the supply chain performance of automotive companies. Technology capability indicators are ranked and prioritized using the fuzzy hierarchical analysis technique. The research method is applied in terms of purpose, is described as the data collection method, and is considered quantitative research. After reviewing the theoretical literature of the research, the drivers of technology capability on the organization's performance were identified for prioritization; they were weighed by a number of experts in the field of automotive companies using questionnaires and fuzzy hierarchical analysis. Indicators and sub-indices of variable technology capability were ranked and prioritized. Based on the results of this research model, it was found that of the eight indicators examined, "strategic technology capability", "product technology capability", and "supplier technology" was the most important, and of the 38 technology capability sub-indicators examined, "technology development" is the most important.

Keywords: Technology capability, Organization performance, Supply chain, Iranian automotive industry, Fuzzy hierarchical analysis.

1 | Introduction

Due to the rapid globalization and the need for companies to compete fiercely in the global arena, technology capability is considered a competitive advantage factor to be present in the worldwide market. Therefore, technology capability is a prerequisite for today's organizations' economic growth, is regarded as a golden key in the business environment, and is an essential weapon in competition between companies [12]. Technology development requires continuous activities rooted in organizational policies and processes and is referred to as technical capability. With the help of technology capability, the necessary infrastructure for investment can be created. Technology also increases production efficiency and consequently increases productivity [37].

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The capability of technology contributes significantly to the promotion and facilitation of trade. Technology capability is an essential factor in increasing competitiveness at the enterprise level. Because it helps businesses gain a competitive advantage by differentiating products, creating new business opportunities, and reducing costs [34]. Technological innovation capabilities are the decisive and fundamental supporting factors of competitive advantage, and the survival and development of modern organizations depend on knowledge, applications, and technological innovation. However, for many organizations, the relationship between investment capability and technological innovation capabilities and how it affects technological innovation capabilities and the firm's competitive performance is still unclear [12].

Technology capability is the efficient application of technological knowledge to create, apply, disseminate, accept and change existing technologies [9]. This concept refers to organized research and development in developed countries and focuses on concepts such as the commercial exploitation of technology. Implementing technology in businesses such as manufacturing companies must be integrated with dynamic areas such as supply chain management. Because this makes it possible to control the management of material resources better, avoid production delays and thus increase compliance with customer demands [33].

An efficient and capable supply chain is also an essential and decisive competitive advantage in a competitive supply chain [19]. The supply chain is a complex network of facilities that design, supply, manufacture, and deliver commodities to customers in the appropriate amounts, locations, and times. The supply chain is highly complex and constantly evolving due to globalization, diversity, flexibility, sustainability, and uncertainty [19].

Companies need to combine technology-related resources with their unique capabilities and lead to superior performance [15]. It is necessary to examine the performance of organizations given the complex and competitive conditions that have arisen over the past few years. Hence, organizations strive to improve their performance to survive and achieve a better position than other organizations. Organizational performance is a multi-dimensional concept of organizational effectiveness and operational efficiency [36]. Organizational performance includes selecting, implementing, and monitoring performance metrics; therefore, organizational efficiency and effectiveness can be based on productivity, effectiveness, service quality, customer satisfaction, and efficiency [18].

Recent research in resource-based perspectives assumes that organizations' performance level varies according to technological capabilities [13]. Organizations in the contemporary world are changing rapidly, and in the current system, improving the performance of the organization is one of the main goals of any organization. Therefore, identifying the variables affecting the performance of organizations and prioritizing and ranking these factors is necessary to improve, upgrade and develop the performance of an organization [16].

Among the many necessities of life, the automotive industry is of great importance and sensitivity in terms of the extent and use of automobiles by different social groups. The automotive industry is one of the most critical industries in the world economy. Due to its wide connection with other industries, it is referred to as the locomotive of industries. For this reason, reviewing its developments and trying to improve the capability of technology and market expansion is one of the essential measures in the domestic and international arena.

Examining the research background and literature, it was discovered that earlier investigations in fuzzy environments and employing hierarchical analysis did not study and analyze the capabilities of technology. Similarly, the capacity of supply chain technology in the automotive industry has not been done in previous research, all of which will be examined in this study.

This research attempts to prioritize and rank the indicators and sub-indicators of technological capability in the automotive industry's supply chain. Consequently, the following research question is posed: what is the relative importance and priority of each of the indicators and sub-indicators of supply chain technological competence that influences the organization's performance in the automotive industry?

According to the structure of the article, after reviewing the theoretical literature of the research, the drivers of technical capability in the supply chain were identified. Then, using fuzzy hierarchical analysis and surveys, several experts in the automotive industry and supply chain weighted these indicators based on pairwise comparisons. The research findings were discussed and then concluded.

2 | Literature Review

2.1 | Theoretical Foundations and Research Background

2.1.1 | Theoretical foundations of research

Some researchers and scholars have provided definitions of technology capability, reflecting their attitude towards their expertise and research areas. The capability of technology is the knowledge used in an effective and productive endeavor. The capability of technology is the tool or method, product, process, physical equipment, or methods by which human capabilities emphasize the machine aspect of technology [27].

One of the driving forces for long-term economic development is technological capabilities. The impacts of technology capabilities have been investigated in national and international studies. Technology capability is related to skill, the knowledge required by the company, acceptance, transfer, and development of the company's technologies. It plays a vital part in achieving productivity in the production process and the degree of innovation of the company [12].

Technology capability can be considered a continuous process of absorbing or producing technology that allows companies to offer distinctive products and services. There are various definitions of technology capability in the research literature, some of which refer to structural factors and others to practical and strategic elements of companies. Some researchers have referred to specific and internal aspects of the company [26]. Some have also referred to the external contexts of companies. Technology capability refers to the ability to absorb, use, accept, apply, transfer and disseminate technology, which includes a set of resources and skills (operational, organizational, and relational) and learning mechanisms. There are two basic approaches to measuring and defining technology capability. The first approach is the process aspect of technological capability, including the set of organizational methods and processes. The second approach is output-oriented, including trade secrets, technological knowledge, and technical knowledge produced by research and development and technological properties such as patents [9].

The three main dimensions of investment capability, production capability, and communication capability are introduced to measure the capability of technology, each of which includes its processes [35].

Technology capability is a factor that differentiates a company from other companies and keeps companies alive [16]. In today's competitive world, maintaining a competitive advantage has become difficult due to the development of markets, competitors' influence, and the presence of different customers. Competitive advantage due to the capability of technology helps to create and maintain companies over time. It can be considered the core of the success or failure of companies compared to competitors [4].

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The efficient evaluation of technological innovation capabilities of enterprises is an essential factor in enhancing competitiveness. In a study, to evaluate and rank the criteria for technological innovation, a framework is proposed and uses a novel hybrid Multiple Criteria Decision Making (MCDM) model to address the dependence relationships of criteria with the aid of the Decision-Making Trial and Evaluation Laboratory (DEMATEL), Analytical Network Process (ANP) and VIKOR. The study reports that the interaction between criteria is essential and influences technological innovation capabilities; furthermore, this ranking development of technological innovation capabilities assessment is also one of the crucial management tools for the management of other related high-tech enterprises [20].

National and regional growth and development models in developing countries, whose development attributes are far different from those of the developed countries, must be in such a way to allow the corresponding country or region to develop at the minimum cost within the shortest possible period. One of the successful approaches toward national and regional development models is relying on a development model based on extending and developing science and technology corridors. This study uses multiple attribute decision-making processes to rank practicable technologies within Isfahan's science and technology corridor. This research's outstanding criteria are applying three decision-making methods for upgrading reliability. For this purpose, 13 attributes were utilized (categorized into six groups). AHP, TOPSIS, and SAW techniques were employed to rank technologies so that the following order of preference was suggested for the practicable technologies within the science and technology corridor of Isfahan: 1) information and communication technology, 2) material technologies, 3) biotechnology, 4) energy technology, 5) Nano-technology, 6) environmental technology, 7) laser and optic technology and 8) nuclear technology [25].

To compete in the global environment, a manufacturing company has to keep developing new technologies. The right technology selection is critical in a successful technology transfer process. However, technology selection is a complex multi-dimensional problem including qualitative and quantitative factors, such as human resources and operational and financial dimensions, which may be in conflict and uncertain. In addition, interdependent relationships exist among various dimensions as well as criteria of technology selection. The identified problems could be solved by combining MCDM methods of different nature and fuzzy set theory. The research objective was to develop a complex approach to evaluate technologies and rank their appropriateness for a company. A hybrid model is proposed based on the Fuzzy Analytic Network Process (FANP) and Fuzzy Technique for Order Preference by Similarity to Ideal Solution (FTOPSIS) [3]. The organization's performance management is a critical component that directly affects the organization's total performance and the competitive environment.

This paper aims to prioritize alternatives related to manager(s) performance in an organization using multi-criteria decision-making, i.e., PROMETHEE, ELECTRE, and TOPSIS, and provide a model for it. The mean Maximum-Minimum Square Ranks method is proposed to combine the results obtained from applying multi-criteria decision-making methods. Also, roadmaps are presented for alternatives with higher priority for the organization. The proposed model allowsfor solving issues related to organizational performance by analyzing various options and criteria for organization manager(s) [1].

Achieving a competitive advantage leads to the competitive dynamics of companies. In a way, the most basic concept of competitive advantage refers to the company's use of resources to achieve superior performance; the three main elements can lead to differentiation and difference compared to other competitors. These factors include sources of competitive advantage, competitive advantage, and company performance [8].

Recently, competitiveness and productivity awareness have increased rapidly among different industries. Hence, the performance evaluation of the productivity criteria is needed to improve productivity and strengthen the organization's management. In this study, a two-phased research method has been projected to determine some governing factors affecting the industry's output. In the first phase, six criteria associated with productivity have been identified based on literature, inputs from experts, and opinions from the officials and managers of six garment industries in Bangladesh. In the second phase, among different MCDM tools, the Fuzzy Analytic Hierarchy Process (FAHP) has been used for evaluating criteria weights and ranking the criteria. The line-balancing criterion is the most critical factor in improving the RMG's productivity [14].

Efficient Inter-Organizational Information Systems (IOIS) have become the backbone of modern supply chains. IOIS can plan, coordinate, collaborate and integrate supply chains to attaina competitive advantage. The speed of innovative technology evolvement, lack of clarity, and delay in taking appropriate managerial and strategic decisions for adopting IOIS demand further research in this area. The robust advancement in digital technologies stresses a proper decision model for the IOIS adoption process. This research provides a novel model for selecting the best IOIS alternative by considering the contents, scope, and critical decision-making factors affecting supply chain integration. Twelve decision-making factors affecting IOIS selection were identified and categorized under four significant dimensions: technological, operational, application, and innovative for effective decision-making [10].

In the context of innovation-driven strategy, the role of suppliers has been attracting much attention. Scientifically selecting an innovative supplier is highly valued by decision-makers. A study focuses on proposing a novel decision framework in the context of collaborative innovation, which helps manufacturers select an innovative supplier who can work hand in hand with them to enhance their innovation performance. First, a novel Capability-Willingness-Risk (C-W-R) evaluation indicator system is established, considering supply risk from a multi-proximity perspective tightly tied to collaborative innovation performance, only thought from geographical proximity in previous supplier selection research. Then a hybrid fuzzy-symmetrical MCDM model is proposed that integrates fuzzy linguistic sets, Best–Worst Method (BWM), Prospect Theory (PT), and VIKOR. This approach obtains a final ranking for innovative supplier selection [22].

A supply chain is an integrated system of interrelated equipment and activities thatdeals with the production process, transfer, and distribution among customers. The fundamental problems in the supply chainare generally divided into three categories: 1) supply chain design, 2) supply chain planning and 3) Supply chain control. In the chain design phase, strategic decisions such as the facilities' location and the appropriate technology selection are taken [31].

Supplier selection is one of the most critical activities of purchasing management in a supply chain. Because selecting suitable suppliers helps reduce purchasing costs, improve the quality of final products and services, etc. In an actual situation, for a supplier selection problem, most input information is not known precisely since decision-making deals with human judgment and comprehension, and its nature includes ambiguity. In fact, on the one hand, deterministic models cannot easily take this vagueness into account. In these cases, the theory of fuzzy sets is one of the best tools to handle uncertainty.

On the other hand, Kavilal et al. [19] proposed a new approach to finding the fuzzy optimal solution to a fully fuzzy linear programming problem. So, this approach in this paper presents a new mixed integer multi-objective linear programming model for the supplier selection problem. Due to the uncertainty of the data, in continuation, we offer a new method to solve multi-objective fully fuzzy mixed integer linear programming and implement the methodologyfor supplier selection problem. Computational results present applying the technique and the proposal-solving method [19].

Supply chain design has always been one of the most critical operational decisions of every organization since the availability of the proper supply system, in addition to reducing system costs, accelerates the delivery and receipt of goods, thereby improving the entire system [5].

The supply chain has been widely discussed in the management literature. In supply chain management, the decision to select a supplier is one of the critical issues made by purchasing and operations managers to maintain the competitive position of organizations. Globalization and outsourcing have added to this competitive pressure to the point where supplier selection has become a vital issue [19].

Nowadays, increasing environmental and social awareness has led numerous industries to adopt Sustainable Supply Chain Management (SSCM). Sustainable Supplier Selection (SSS) is a significant and primary step in achieving an SSCM. SSS is an MCDM problem and is very intricate in its nature. This study aims to evaluate and rank sustainable suppliers using Data Envelopment Analysis (DEA), a popular model for measuring the productive efficiency of decision-making units effectively and can also handle MCDM problems. An evolutionary algorithm, Differential Evolution (DE), is used to solve the DEA model, avoiding some inherent limitations of DEA. This integrated DEA-DE model provides more accurate efficiencies. Employing this easy and fast model to assess sustainable suppliers will help industries and suppliers move towards achieving and maintaining sustainability and thus will increase the overall performance of SSCM [28].

2.1.2 | Empirical background of the research

In a study, researchers examined the impact of technology capability flexibility infrastructures on the competitive advantage of small, medium, and large companies. According to the findings of this study, having a flexible technology infrastructure positively impacts competitive advantage [21].

The investigation of competitive strategy, technical capabilities, and organizational performance in the manufacturing industry revealed that technological capabilities influence organizational performance and can contribute to competitive advantage [27].

According to a study, technology capabilities refer to the company's internal competencies or relative strength compared to other companies. Companies' technological capabilities are strongly tied to their technological innovation. Technology capabilities depend on how the company has performed in the past and are likely to lead to a successful path. Technology capabilities can increase the value of the company by using external knowledge. High-tech companies have a high motivation to acquire knowledge, unite and mobilize resources, and these companies have an increased ability to benefit from external resources [34].

Researchers examined the impact of technology on supply chain performance. The findings revealed that technological capabilities enhance logistics efficiency, operational efficiency, customer communication, proper communication with suppliers, and competitive advantage. The final results indicate that creating the correct supply chain is critical to getting a competitive edge [35].

According to a study by De Mori et al. [9], technology's capabilityis vital in achieving productivity in the production process. The degree of innovation of the company, which is associated with skills, the amount of knowledge required to accept the company, acceptance, transfer, and the development of company technologies, is relevant and serves as a channel to solve companies' problems. Technology capability can be used as a quantitative and qualitative criterion for solving problems. Technological capability can be a tool for analyzing performance and making decisions and a source of technology dynamism in an organization [9].

Collaborating with six institutes in the Netherlands, Norway, the United Kingdom, and Italy presented an integrated model for assessing technology capability. Different functional layers were examined in this model, which was implemented in health care. Finally, by offering an integrated evaluation model of Gerhados technology, a comprehensive approach to the systematic evaluation of technology has been suggested [7].

In a study by Radfar and Khamseh [30], they introduced the model of technology needs. This model identifies and determines the capabilities needed to implement technology priorities in developing countries. Through this model, the capabilities of firms are measured from 3 dimensions based on a questionnaire that, after completing it by experts, their scores are added together, and the total score is compared with the table related to the form of determining the results of technology needs assessment and finally between four levels. In terms of capability (firm type I: passive, firm type II: reactive, firm type III: strategic, firm type IV: creative), the level of capability of the firm is determined [30].

In a study by Mikalef and Pateli [23], they examined the dynamic capabilities of technology and its impact on competitive performance. The results showed that dynamic technology capabilities affect operational and market capital agility, and technology capabilities indirectly affect competitive performance [23].

Dynamic capabilities, creativity and innovation capabilities and their impact on competitive advantage and company performance

The role of adjusting entrepreneurial orientation is the focus of a study. This study defines dynamic ability as the ability for systematic problem-solving that varies with the desire to detect opportunities and threats, make timely decisions, and effectively implement strategic decisions, ensuring the appropriate direction. In addition, the two-way viewpoint investigates the indirect influence of exploitation and exploration capabilities via creativity and innovation capabilities, providing proof of the impact on a company's competitive advantage and performance [12].

Research on technology capability, environmental innovation performance, and collaborative research and development strategies in the new energy vehicle industry: evidence from Chinese companies. The study is based on a unique collection of panel data from 127 companies in China's automotive industry from 2009 to 2018. Empirical findings show that firm-level technology capability is positively correlated with the performance of environmental innovations, and government ownership is enhanced. Surprisingly, this positive relationship weakens the increase in government subsidies. The results also show that companies with higher technological capabilities prefer collaborative R&D. In comparison, companies with lower technical capabilities tend to have in-house R&D. These findings increase the understanding of the cost-effectiveness of R&D investment in the energy technology industry and shed light on the interaction of internal and external resources. This study presents management concepts to promote industry prosperity [37].

In a study by Qin et al. [29], they researched the impact of technology capability and infrastructure capability on new product development performance, market knowledge's role, and innovation's formalization process. This study shows how the capacity of technology infrastructure affects the implementation of new product development by considering market knowledge as a mediator and innovation processes as a moderator. The study provides empirical evidence that technology infrastructure capability is not only directly and positively related to new product development performance but also indirectly related to the use of market knowledge. Further results show that the formal innovation process weakens this relationship. Overall, this study expands the understanding of how technology infrastructure capability affects new product development performance and can be helpful for managers looking for superior recent product development performance [29].

In the current intense competitive environment, companies continuously need to increase their performance and adapt their activities to the developing and changing environment to survive. The concepts of quality, technology, and innovation are among the most prominent issues in this competitive environment. At this point, recently emphasized information technologies integrated into the business, innovation activities, and logistics services that develop along with these activities are essential issues. Accordingly, this study aims to reveal the role of information technology use in supply chain innovation and logistics service quality. According to the results, it has been determined that information technologies mediate between innovation capability in the supply chain and logistics service quality [2].

3 | Research Methodology

The present study is applied in terms of purpose and is considered quantitative research. Also, in terms of the data collection method, it is "descriptive (non-experimental)", which is regarded as a survey-single-section type due to the use of the fuzzy hierarchical analysis method [32].

The statistical population in this study is domestic car companies, Iran Khodro Industrial Group, and Saipa Automotive Group and their supply chain. A questionnaire was designed to compare the main dimensions of "technology capability" and compare sub-indicators of each dimension, which was agreed upon by ten experts in the field of automotive and supply chain at management levels with at least five years of experience and master's degree and above, it was answered. Statistical samples of this study were selected as snowballs (chain reference). The fuzzy hierarchical analysis process was used to weigh the identified indicators.

According to *Table 1*, the main elements of the model are identified along with the variables and technology capability items in the supply chain. After the initial design of the model, through reviewing the research literature, the content validity of technology capability was assessed by surveying professors and experts in the field of the automotive supply chain; in this way, a questionnaire consisting of identified components was provided to the experts, and they were asked to rate the relevant details based on a nine-point Likert scale. Also, at the end of the questionnaire, space was considered to comment on the components not mentioned in the questionnaire. Finally, factors with a score of more than 5 or 7 were selected. The main items of the questionnaire for the second-order hidden variable of the model are presented in *Table 1*.

Table 1. The analytical research model for supply chain technology capability.

Variable	Code	Item	References
Product technology capability (A)	A1	Technology creation	[13], [15]
	A2	Technology transfer	[13], [15]
	A3	Implementation and application of technology	[9], [34]
	A4	Cost savings by technology	[12], [26]
	A5	Update and use technology	[12], [27]
Process technology capability (B)	B1	Process efficiency by technology	[9], [34]
	B2	Improving service delivery by technology	[27], [30]
	B3	Reduce process time	[13], [37]
	B4	Reduce operating costs	[34], [37]
	B5	Compliance of production with engineering specifications	[12], [37]
Supplier technology and supply chain (C)	C1	The extent of technology knowledge absorption	[12], [34]
	C2	Acceptance of new technologies	[15], [35]
	C3	Technology transfer and development	[30], [34]
	C4	Operational effectiveness	[19], [33]
	C5	Improve logistics efficiency	[19], [33]
The capability of core and backup activities (D)	D1	Infrastructure development	[12], [37]
	D2	Upgrading the human resource management system	[16], [36]
	D3	Supporting technology development	[12], [37]
	D4	Supply and supply of technology needs	[9], [30]
	D5	Financing for technology development	[34], [37]
Tools and skills (E)	E1	Proper organization and management in line with technology	[12], [30]
	E2	Utilization of new production machines and tools	[9], [12]
	E3	Improving human resource skills and experiences	[16], [36]
	E4	Examine the limitations in the use of technology	[37]
	E5	Increase the amount of information and technical knowledge	[21], [29]
Tools and skills (E)	F1	Develop a vision and strategy for technology innovation	[12], [37]
	F2	Identify internal strengths and weaknesses and external technological opportunities and threats	[12], [37]
	F3	Technology-based performance support	[15], [34]
	F4	Technology development	[12], [37]

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Table 1. Continued.

Variable	Code	Item	References
Investment capability (G)	G1	Optimal allocation of capital	[18], [37]
	G2	Purchase of intangible technology such as licenses and patents	[36], [37]
	G3	Adequate purchase of tangible technology such as equipment and machinery	[33], [37]
	G4	Allocate a share of revenue to research and development	[15], [37]
Organizational capabilities (H)	H1	Reproduction and expansion of technology	[8]
	H2	Maintain existing technologies	[26]
	H3	Technology monitoring	[9]
	H4	Adaptation and improvement of technology	[12], [15]

3.1 | Fuzzy Hierarchical Analysis Process Method

The fuzzy hierarchical analysis is used to measure the technology capability model. The traditional hierarchical analysis process does not fully reflect the human thinking style. In other words, fuzzy sets are more compatible with linguistic and sometimes ambiguous human explanations, so it is better to use fuzzy sets (using fuzzy numbers) to make long-term predictions and decisions in the real world. The fuzzy hierarchical process [6] method is used in this research.

In the fuzzy hierarchical analysis technique, a pairwise comparison of each model level's elements must be performed after drawing the hierarchical decision tree. In the calculation stage, the coefficients of each pairwise comparison matrix are calculated using the definitions and concepts of fuzzy hierarchical analysis. For each row of the pairwise comparison matrix, the value of SK, which is itself a triangular fuzzy number, is obtained from *Eq. (1)*. *Eqs. (2)* to *(4)* calculate each part of this relationship.

$$S_k = \sum_{j=1}^{n} M_{ki}^{j} \otimes \left[\sum_{i=1}^{m} \sum_{j=1}^{n} M_{ij}\right]^{-1}. \tag{1}$$

$$\sum_{j=1}^{m} M_{ij} = \left(\sum_{i=1}^{m} l_j, \sum_{i=1}^{m} m_j \sum_{i=1}^{m} u_j\right), \quad i = 1,2, \dots, m. \tag{2}$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} M_{ij} = \sum_{i}^{n} l_i, \sum_{i}^{n} m_i \sum_{i}^{n} u_i). \tag{3}$$

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{ki}^{j}\right]^{-1} = \left[\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right]. \tag{4}$$

After calculating all the Sk, in this step, we have to calculate the magnitude of each surface element on the other elements of that level separately, according to the following equations:

$$\begin{cases} V\ M_1 \geq M_2) = 1, & \text{if } m_1 \geq m_2, \\ V\ M_1 \geq M_2) = 0, & \text{if } l_2 \geq u_1, \\ V\ M_1 \geq M_2) = hgt\ \ M_1 \cap M_2), & \text{otherwise.} \end{cases} \tag{5}$$

$$hgt\ \ M_1 \cap M_2) = \frac{l_2 - u_1}{m_1 - u_1) - \ m_2 - l_2)}. \tag{6}$$

The magnitude of a triangular fuzzy number is obtained from k of another triangular fuzzy number from *Eq. (7)*:

$$V\ M_1 \geq M_2, \dots, M_k) = V\ M_1 \geq M_2) \text{ and } \dots \text{ and } V\ M_1 \geq M_k). \tag{7}$$

To calculate the weight of the indices in the matrix of pairwise comparisons, we do the following:

$$W'\ x_i) = \{V(S_i \geq S_k)\}, \qquad k = 1,2, \dots, n, k \neq i. \tag{8}$$

Therefore, the weight vector of the indices will be in the form of *Relation (9)* or the same vector of abnormal coefficients of fuzzy hierarchical analysis.

$$w' = [w'\ x_1), w'\ x_2), \dots, w'\ x_n)]^t. \tag{9}$$

3.2 | Calculate the Compatibility of Fuzzy Pairwise Comparison Matrices

Deng [11] proposed a method for calculating the degree of compatibility of paired fuzzy comparison matrices based on strong transmittance conditions. In this method, to investigate the compatibility conditions, it is necessary to form two separate matrices Ag and Am from each pair comparison matrix $\tilde{A}(n \times n)$. The matrix Am is obtained from the median values of the preferences of each expert (median values of fuzzy triangular numbers). (Am = [aijm]) the second matrix (Ag) is created from the geometric mean of the upper limit and the lower limit of fuzzy triangular numbers (*Eq. (10)*).

$$A^g = \sqrt{a_{ijI}.\, a_{ijU}}. \tag{10}$$

The weight vector of each of these two matrices must be calculated to find the degree of compatibility. Because these matrices contain non-fuzzy data, the Saaty method can be used to calculate the weight vector. Hence, the vectors Wg and Wm are obtained from *Eqs. (11)* and *(12)*.

$$w^m = [w_i^m] \quad \text{where} \quad w_i^m = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ijm}}{\sum_{i=1}^{n} a_{ijm}}. \tag{11}$$

$$w^g = [w_i^g] \quad \text{where} \quad w_i^g = \frac{1}{n}\sum_{j=1}^{n}\frac{\sqrt{a_{ijL}.a_{ijU}}}{\sum_{i=1}^{n}\sqrt{a_{ijL}.a_{ijU}}}. \tag{12}$$

n is the dimension of the matrix. Each matrix's largest special amount (λmax) is calculated from *Eqs. (13)* and *(14)*.

$$\lambda_{max}^m = \frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ijm}\left(w_j^m / w_i^m\right). \tag{13}$$

$$\lambda_{max}^g = \frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{n}\sqrt{a_{ijL}.\, a_{ijU}}\left(w_j^g / w_i^g\right). \tag{14}$$

Based on the Saaty method, the Consistency Index (CI) for measuring the reliability of the first questionnaire, which shows the deviation from full compliance, is obtained in the following order:

$$CI^m = \frac{\lambda_{max}^m - n)}{n-1)}. \tag{15}$$

$$CI^g = \frac{(\lambda_{max}^g - n)}{n-1)}. \tag{16}$$

$$CR = \frac{CI}{RI}. \tag{17}$$

Table 2. Random indices of Deng.

Matrix Size	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Rm	0	0	0.489	0.793	1.072	1.199	1.287	1.341	1.379	1.409	1.418	1.446	1.455	1.491	1.499
Rg	0	0	0.179	0.262	0.359	0.381	0.4090	0.416	0.4348	0.445	0.453	0.477	0.469	0.480	0.488

If both (CRm and CRg) compatibility values of each pairwise comparison matrix are greater than 0.1, the expert should be asked to reconsider their preferences. Suppose only CRm or CRg is greater than 0.1, and another is acceptable in the set. In that case, it is better to persuade the decision maker to re-evaluate the intermediate values and keep the limit values unchanged, but given that in this study of standard Chang triangular fuzzy numbers, which has a special relationship between the lower limit, the median value and the upper limit of each number, is used. In case of incompatibility of either of these two matrices, the preferences of the respective matrix should be reconsidered in general.

4 | Research Findings

After studying the research literature and identifying the drivers of technical capability in the automotive industry supply chain, the recognized model serves as the foundation for fuzzy hierarchical analysis, and the weighting of the model's indicators and sub-indices are examined.

The pairwise comparison questionnaire of the main dimensions of "technology capability" and the comparisons of the sub-indicators of each dimension was provided to several experts in the automotive industry and supply chain. It was decided to answer the questionnaire in an agreed manner. Technology competency indicators were weighed through a hierarchical process and questionnaire data. The fuzzy hierarchical process method was obtained by formulating the final pairwise comparison matrices in matrix Excel software. The final weighting of the indices was calculated by multiplying the weight obtained by each index in its subgroup in the respective next weight. The incompatibility of each pair of comparison tables was individually calculated (the incompatibility of each matrix should be less than 0.1) to test the questionnaire's reliability (to determine the compatibility or incompatibility of opinions).

The final weight of each sub-index in the whole technology capability model is obtained by using the importance of the main index multiplied by the weight of the sub-index in their group. The final weight obtained for each sub-index and their priority and rank among the indicators of the technology capability model is described in *Table 3*.

Table 3. Weights and ranks of indicators and sub-indicators of the technology capability model.

The Main Indicator	Index Rank	Sub-Index Rank	Subscript	Weight of the Main Indicators	Sub Weight Index
Product technology capability (A)	2	4	A1	0.228	0.098
		5	A2		0.065
		1	A3		0.421
		3	A4		0.199
		2	A5		0.215
Process technology capability (B)	7	1	B1	0.035	0.379
		3	B2		0.175
		4	B3		0.096
		5	B4		0.067
		2	B5		0.281
Supplier technology and supply chain (C)	3	3	C1	0.153	0.152
		2	C2		0.291
		1	C3		0.394
		4	C4		0.095
		5	C5		0.067
The capability of core and backup activities (D)	8	1	D1	0.024	0.405
		2	D2		0.253
		3	D3		0.178
		4	D4		0.096
		5	D5		0.067
Tools and skills (E)	5	2	E1	0.108	0.269
		1	E2		0.408
		4	E3		0.091
		3	E4		0.162
		5	E5		0.068
The strategic capability of technology (F)	1	2	F1	0.263	0.257
		3	F2		0.150
		4	F3		0.093
		1	F4		0.498
Investment capability (G)	6	1	G1	0.045	0.429
		3	G2		0.143
		4	G3		0.092
		2	G4		0.334
Organizational capabilities (H)	4	2	H1	0.144	0.257
		3	H2		0.155
		1	H3		0.415
		4	H4		0.113
		5	H5		0.058

According to the results of the fuzzy hierarchical analysis process and the data in *Table 3*, the dimension of "strategic capability of technology," with a weight of 0.263, had the highest score. The final weights of the sub-index are 0.498 for "technology development," 0.257 for "development of vision and strategy for technology innovation," respectively, "identification of internal strengths and weaknesses and external opportunities and threats of technology." Equivalent to 0.150, "technology-based performance support" equals 0.093.

Next, "product technology capability" gained the weight of 0.228 in second place. The final weight of the sub-indices for "implementation and application of technology" is equal to 0.421, "update and use of technology" are equal to 0.215, "cost saving" is equal to 0.199, "technology creation" was equal to 0.098, and "technology transfer" was equal to 0.065.

According to *Table 3*, the "supplier technology and supply chain" dimension weighs 0.153. The final weights of the sub-indices are "technology transfer and development" equal to 0.394, "acceptance of new technologies" equal to 0.291, "technology knowledge absorption rate" equal to 0.152, and "operational effectiveness," respectively. Equal to 0.095, "improvement of logistic efficiency" is equal to 0.067.

Similarly, the weight of the following "organizational capabilities" was calculated to be 0.144 percent. The final weights of the sub-indices are equal to 0.415 for "technology monitoring," 0.257 for "technology reproduction and expansion," 0.155 for "maintenance of existing technology," and "adaptation and improvement of technology," respectively. With 0.113, the "ability to update technology" was equal to 0.058.

For the "tools and skills" dimension, a weight of 0.108% was obtained. The final weight of the sub-indices for "use of new production machines and tools" is equal to 0.408, respectively, "proper organization and management in terms of technology" is equal to 0.269, and "examination of limitations in the use of technology" is equal to 0.162, "improvement of skills and experiences of human resources" equal to 0.091, "increase of information and technical knowledge" equal to 0.068.

Then "investment capability" gained a weight of 0.045 percent. The final weight of the sub-indices for "optimal allocation of capital" is equal to 0.429, "allocation of revenue share to research and development" equal to 0.334, respectively, "purchase of intangible technologies such as licenses and patents" equal to 0.143, "adequate purchase of tangible technology such as equipment and machinery "equal to 0.092.

Next, "process technology capability" gained a weight of 0.035 percent. The final weight of the sub-indices for "process efficiency by technology" is equal to 0.379, "compliance of production with engineering specifications" is equal to 0.281, "improvement of service delivery by technology" is equal to 0.175, and "reduction of process time," respectively. Equivalent to 0.096, the "reduction of operating costs" was equal to 0.067.

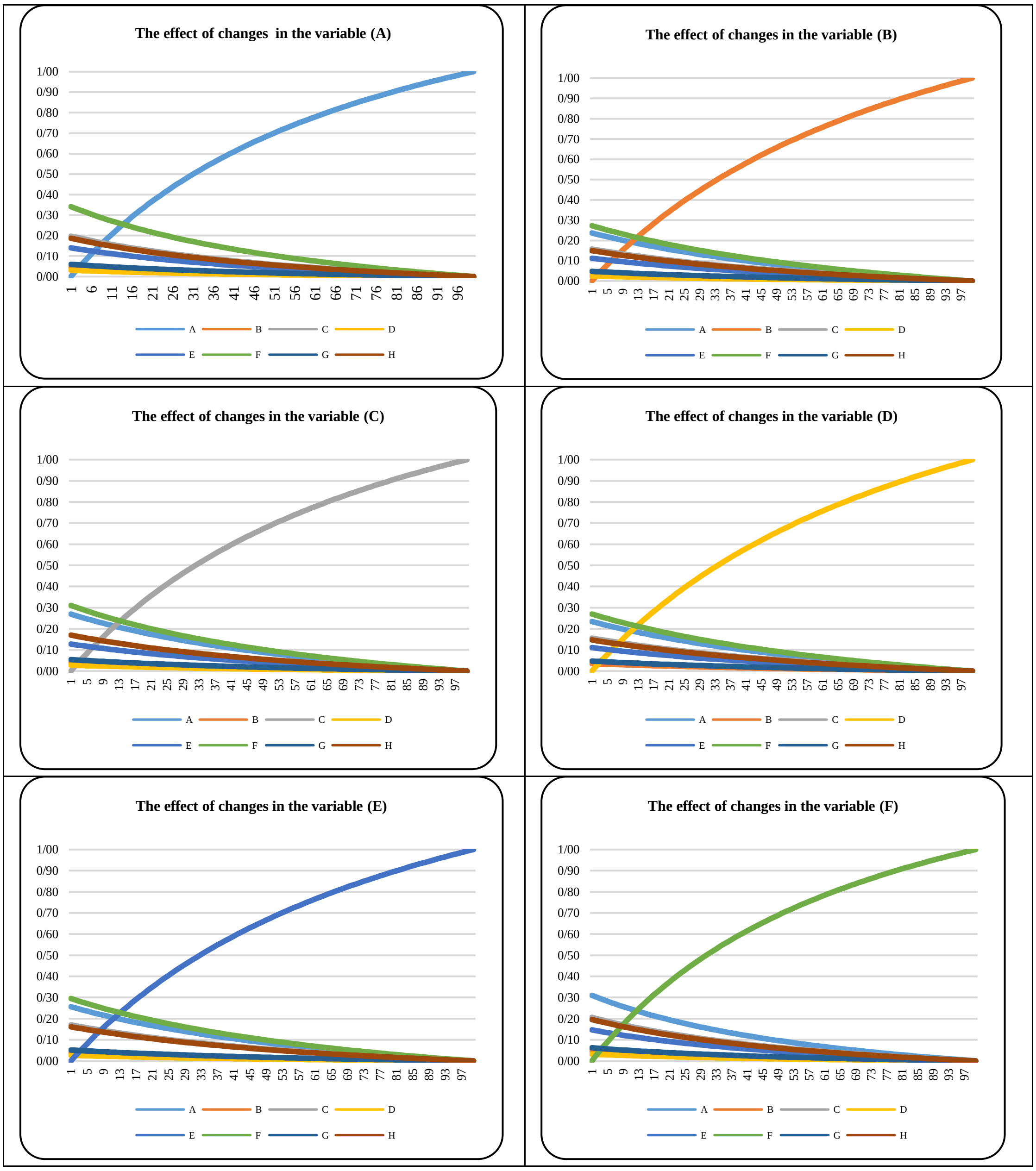
Finally, according to *Table 3*, the "capacity of main and support activities" gained a weight of 0.024 percent. The final weight of the sub-indices for "infrastructure development" is equal to 0.405, "upgrade of human resource management system" is equal to 0.253, "support for technology development" is equal to 0.178, "supply and supply of technology needs"are equal to 0.096, "financing for technology development" was equal to 0.067.

4.1 | Sensitivity Analysis

Sensitivity analysis approaches can be divided into two categories: deterministic and probabilistic, which are sometimes known as local and general approaches. The deterministic sensitivity analysis method is usually used if the model is very complex. In this case, the model with a small number of analyzes, with different combinations of parameters, one of which changes each time, and their effect on the outputs is measured by initial analysis. Sensitivity analysis (parameter-induced) determines the crucial parameters of the model and their relative importance [17].

The terms uncertainty analysis and sensitivity analysis usually come together and are likely to overlap. The purpose of parameter sensitivity analysis is to determine the critical parameters of the model and their relative importance. For example, is parameter a more urgent than parameter B? Or what is their significance to C? In other words, can the parameters be ranked in order of importance? [24].

In the proposed sensitivity analysis, each variable starts to change from 0 to 100%, and the effect of these changes on other variables in the study is investigated. Due to the complexity of the relationship between the variables, there will always be a nonlinear relationship between the changes. Super decision software is used for analysis. It has been shown in all diagrams that the criteria with a higher weight will accept the highest slope of changes from the increasing trend of the growing variable, and the less critical variables will tend to zero with a lower slope.



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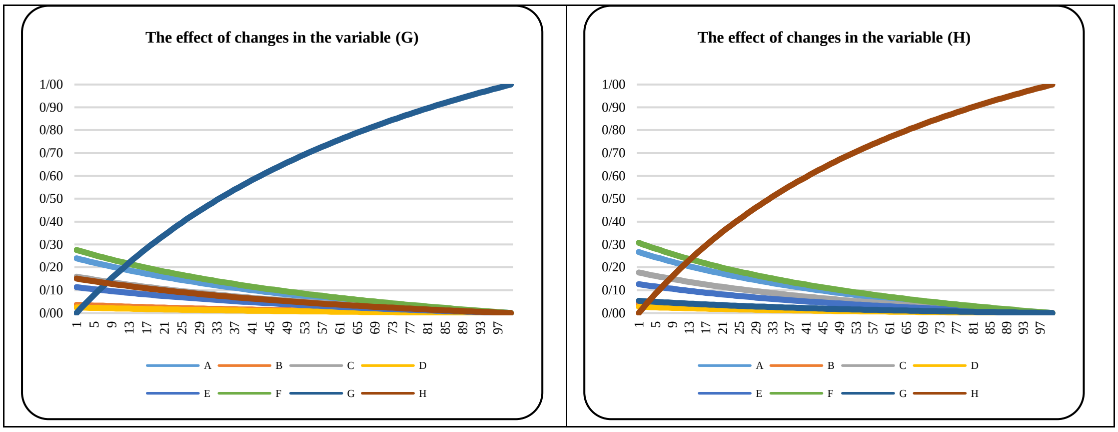

Fig. 1. Sensitivity analysis.

5 | Discussions and Conclusions

This study shows new drivers and relationships beyond existing literature. After analysis, we got some results different from the past. This study contributes to the literature in the following ways. The first is the definition and dimensions of technology capabilities. The second contribution is the empirical corroboration that technology capabilities are also relevant for the Iran industry.

The literature suggests that Western-generated theories may not fully apply to societies with vastly different socioeconomic conditions. Third, this study contributes to the debates on the value of technology capabilities.

The finding shows that technology capabilities enable firms to be sensitive to opportunities and threats, seize possible chances and implement the change necessary to enhance environmental adaptability and ultimately achieve competitive advantage.

The result of this study suggests a high priority for the identified drivers: "strategic technology capability" and "product technology capability" in the main criteria and "technology development" and "implementation and application of technology" in the sub-criteria.

Researchers in previous studies have proposed various drivers. For example, the driver of "flexible technology infrastructure" [21], "internal competence and competence or relative strength of the company to other companies" [34], the driver of "appropriate supply chain" [35], the driver "providing a comprehensive approach" [7], "technology model" [18], "operational agility and capital agility" driver [23], "dynamic capability" [12], also suggested "environmental innovation performance"driver by Wu et al. [37] and finally, "technology capability infrastructure capability" [29].

New drivers have been identified and prioritized in the study, which has not been mentioned in previous studies, and by considering the mentioned drivers, new results can be obtained.

The results of this study increase our awareness of the propulsion indicators of the supply chain technology capability model and highlight the importance of each of these indicators. Based on the results of the fuzzy hierarchical analysis method for the indicators of the supply chain technology capability model, the following items are presented:

Regarding key metrics, automakers in the supply chain need to pay more attention to the "strategic technology capability" issue. Based on the results, manufacturers should put the main criterion of "strategic technology capability" on the agenda and review it. The adoption of these strategies, along with other strategies and various policies in various industrial dimensions, has played a significant role in the relative advancement of industries. Some of these strategies are reverse value chain strategy, reverse life cycle strategy, process expertise strategy, product technology pioneering strategy, and pioneering strategy in applying new technologies. Organizations need to improve "technology development leadership." There are two ways to design a successful model for technology development and commercialization. First, reviewing and analyzing the behavioral models and implementation of successful technologies developed and commercialized and modeling them, and second, recognizing the process of technology development and commercialization and systematically reviewing its literature to formulate the technology development process. "Developing a vision and strategy for technological innovation" is the next priority for improvement. For this purpose, the organization can formulate a vision and strategy in the areas of strategic innovation in the market, strategic innovation in the product, strategic innovation in organizational processes, strategic innovation in organizational structure, strategic innovation in human resource development, strategic innovation in customer relations and strategic creation of organizational plan and action. "Identifying internal strengths and weaknesses and external opportunities and threats of technology" is of secondary importance. In the next priority, special attention should be paid to the "performance-based technology support" index and creating well-codified monitoring programs.

The next priority is the "product technology capability" index. In this section, manufacturing companies are suggested to pay special attention to the "implementation and application of technology." For this purpose, six tools of patent analysis, portfolio management, roadmap development, S curve, port stage, and value analysis can be used to create, implement, and apply technology within the organization. In the "supplier technology and supply chain" field, there is a need to focus on the "technology transfer and development" sub-index. Technology transfer and development can be considered the process of using existing technologies to create innovations and new products. Transferring scientific and technical findings from one organization to another promotes the level of development and commercialization. Applying an organized and orderly procedure for technology transfer and development transforms this process from a rare and random event into a structured one. This can bring significant value to emerging industries, especially in critical technologies. To achieve this value, it is necessary to fully understand the technology transfer process and apply it properly in the organization. The "capabilities of the organization" criterion should develop specialized programs for "technology monitoring."

At the beginning of the research, after reviewing the literature and identifying technology capability indicators through content validity, the indicators extracted by selected experts in the automotive industry supply chain field were approved. Data analysis was performed using Excel software, and the priority of the main variables was determined as follows:

Similarly, the sub-indices related to the main variables were also prioritized in the following order:

- *Strategic technology capability: leading technology development; developing a vision and strategy for technology innovation; identifying internal strengths and weaknesses and external technological opportunities and threats; technology-based performance support.*
- *Product technology capability: implementation and application of technology; update and use of technology; save money; technology creation and transfer.*
- *Technology suppliers and supply chain: technology transfer and development; acceptance of new technologies; the extent of technology knowledge absorption; operational effectiveness; improving logistical efficiency.*
- *Tools and skills: using new production machines and tools; proper organization and management in the direction of technology; examining the limitations in using technology; improving human resource skills and experiences; increasing the amount of information and technical knowledge.*
- *Organizational capabilities: technology supervision; reproduction and expansion of technology; maintenance of existing technology; adaptation and improvement of technology; capability and technology updates.*
- *Investment capability: optimal capital allocation; allocate a share of revenue to research and development; purchase of intangible technology such as licenses and patents; adequate purchase of tangible technology such as equipment and machinery.*

- *Process technology capability: process efficiency by technology; compliance of production with engineering specifications; improving service delivery by technology; reducing process time; reducing operating costs.*
- *The capability of core and support activities: infrastructure development; improving the human resource management system; supporting technology development; procurement and supply of technology needs; financing for technology development.*

During the research period, researchers encountered several limitations, including limitations related to the research design, such as the impossibility of identifying all the factors influencing the research design, and limitations and lack of similar research that directly addresses the research topic, as well as constraints related to the effectiveness of research due to conducting research in the automotive industry and its specific community, which can limit the generalizability of the findings. It also mentioned the limitations of statistical research methods, such as weaknesses in research tools (for example, the fuzzy hierarchical analysis method has limitations and disadvantages) and the lack of cooperation of some people to complete the questionnaire.

Conflict of Interest

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

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