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A New Model for Balancing between Asset Sharing Risk and Responsiveness: Developing the Augmented Ɛ-Constraint Method

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Abstract

In recent years, responsiveness in the Supply Chain Network (SCN) has been considered to improve competitiveness because customers are the most significant part of a supply chain, and promptly meeting customer demand is substantial. In this article, to deal with the technological risks, the Reinforcement Policy (RP) before the disruption and the Assets-Sharing (AS) policy before and after the disruption has been used as Resilience Policies for Disruption (RPD). Also, the responsiveness of the network, as well as the risks associated with AS, have been considered in mathematical modeling. In addition, Lateral Sending (LS), delivery time deviations, and penalties for lost sales for increasing customer satisfaction in the cost objective function are considered responsiveness policies. A solution method has been developed based on the augmented ε-constraint to solve the model. Finally, the results show an improvement in cost by up to 14% and responsiveness by up to 17% by using the proposed policies, as well as the effectiveness of the developed technique to cope with the Multi-Objective (MO) model.

Keywords: Aghezzaf's method, Supply chain, Augmented ε-constraint, Responsiveness policies, Delivery time.

1 | Introdction

The vulnerability of the Supply Chain Network (SCN) due to risks has caused researchers to pay attention to this issue and introduce the 5th industrial revolution [1]. Some risks, such as uncertainties or disruption risks in SCN management, have been emphasized in the 5th industry [2]. These risks can sometimes severely affect the production and distribution system of products and lead to the loss of reputation or income of an organization. For this reason, organizations focus on strengthening their chain and try to fulfill the customer's demands on time [3].

The existence of risks and their impacts on the business environment and considering customer needs in supply chains caused organizations to pay attention to reducing product delivery time, increasing responsiveness, and focusing on meeting customers. Assets-Sharing (AS) between SCN members can play a significant role in achieving these goals [4]. Data sharing can lead to the reduction of lead time and obtaining accurate information and thus increase the level of

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responsiveness. Also, AS can adjust the inventory level, reduce costs, and prevent lost sales. So, AS, as a solution to minimize uncertainty risks, and to increase customer responsiveness, is used [5].

Also, various solutions have been presented to reduce the effect of disruption on the responsiveness of the SCN and timely satisfy customers' products. For example, researchers have provided solutions such as RP [6] or increasing responsiveness after disruption by using resource urgency to meet potential shortages [7]. One of the practical solutions to improve the responsiveness of the SCN is the use of AS [8].

AS in the SCN increases the speed of recovery and delivery of goods to customers after disruption and can increase customer service and responsiveness [8]. Nowadays, in competitive markets, the proper response to customers is essential; taking measures alone to increase response has less effect than when companies have AS [9]. For example, sharing knowledge and experience before the disruption, cooperating in supplying demand on time, and preventing the loss of customer demand after the disruption can effectively reduce the effects of risks in the SCN [8]. Therefore, instead of working alone, all supply chain members should work together to increase responsiveness [9]. Due to the increase in demand and the challenges that may arise from keeping inventory for the organization, the best way to reduce costs is AS because SCN members can AS such as warehouses, workforce, and transportation to reduce costs [9]. Also, the AS, such as data and knowledge between SCN members, will lead to a strong commitment to meet customer needs and increase responsiveness [9]. For this reason, researchers have presented different ways to use AS in reducing SCN risks [10], [11].

AS can create some risks; for example, the AS and information of the organization cause opportunistic risks, or AS leads to communication with partners with a lower level of capability [12]. So AS, in these cases, increases the delivery time and causes additional costs for the organization. The risks of joint work are also classified among SCN members [13].

In this article, the mathematical model has considered AS and Lateral Sending (LS) to increase responsiveness in the Steel Supply Chain (SSC). In addition, a new Multi-Objective (MO) model with responsiveness policies has been presented, in which the objective functions are cost, responsiveness, and AS risk. New stochastic optimization based on maximum deviation has been used to deal with uncertainty risks such as changing processing time and demand. Finally, a solution method based on the augmented ε-constraint way has been developed and applied to solve the MO model.

The rest of the study is as follows. In the next section, the related work is evaluated. Section 3 elaborates on the stochastic model and the augmented ε-constraint method for the MO model. In Section 4, related information is applied to the mathematical model, and the results are explained. Finally, the research findings are presented in the last section.

2 | Literature Review

There are many studies on the role of responsiveness in SCN and logistics. Richey et al. [3] reviewed the related works and concepts. One of the primary researches regarding the consideration of responsiveness in the design of the SCN is associated with the study of [14], in which the amount of responsiveness to the customer is maximized. Next, the authors defined the response rate as an objective function maximized in a MO mathematical model [15]. Martí et al. [16] presented a model balancing customer responsiveness and carbon dioxide output. Hamidieh et al. [17] proposed a model for designing a closed-loop SCN in which the speed of responding to customers in uncertainty is optimal. In the paper by [18], a responsiveness level for each customer is considered, and optimization of other variables is done according to these levels. Aboolian et al. [19] developed models in responsive SCN design and considered responsiveness in the network in two ways. First, they considered the responsiveness in the limitation. Second, for the delay in meeting the customer's demand, they determined the penalty, which is tried to be minimized in the mathematical model. Azaron et al. [20] presented a model in which the customers' travel to satisfy their demand is underrated as a responsiveness and objective cost function. In papers presented by Nayeri et al. [21] and Vali-Siar and Roghanian [22], the responsiveness rate is considered a limitation in the mathematical model, which should not be less than a particular value. Hamidieh and Johari [23] presented a method for reliable-responsive blood SCN. Ghasemi et al. [24] formulated a MO model and considered a time window for each customer so that reliability for delivering products timely to the customers is maximized.

Many works have been done regarding theoretical concepts and AS approaches in the SCN, and there are fewer studies on the quantitative modeling of AS in the SCN. Singh et al. [4] have explained the relevant concepts and future research in this context. Regarding quantitative studies, one of the primary research in AS is presented by [25], in which the role of AS in the SCN was investigated, and it was shown that AS decreases the SCN cost. Some authors have evaluated the role of AS in SCN transportation. For example, Ballot and Fontane [26], Pan et al. [27], and Sugiono et al. [28] investigated how to optimize capacity or vehicle sharing and routing in the transportation network. Some authors have also discussed the role of facility sharing in reducing costs and increasing sustainability in the SCN. For example, you can refer to [29]–[31], which evaluated positive economic, social, and environmental effects on the AS in SCN. Also, the problem of optimization of hub places in different SCNs under uncertainty in costs is addressed by Habibi et al. [32]. A model to optimize the strategic alliance network is presented by [33], in which the partners are determined to minimize the total cost of the entire network. A green model for the SCN design in the article by Foroozesh et al. [34] is presented to reduce the effects of disruption on the network in the mathematical model, and the LS of products in distribution centers is considered. Dorgham et al. [35] used collaboration to reduce transportation costs in the hospital SCN and developed a linear planning model considering fuzzy demand. In another research, by considering the scenarios of cooperation and non-cooperation in the design of the SCN, Mrabti et al. [36] presented a model to reduce the cost and amount of carbon dioxide gas and the performance of AS in a distribution network in France. Ghahremani Nahr and Zahedi [37] formulated a new information-sharing model in two levels of the SCN under uncertainty.

By reviewing the related works to AS, it is extracted that although some studies, such as [10], [11], considered AS in SCN risk mitigation, some authors, such as Mafini and Muposhi [12] and Tang [38], stated that due to the losing data and the inappropriate of colleagues, companies are often reluctant to AS. Also, they introduce data theft as the AS risk in the SCN.

Resilience in the SCN refers to the ability of the SCN to reach the desired level of disruption [39]. Resilience Policies for Disruption (RPD) in the SCN include policies before and after the disruption [7]. Xames et al. [40] investigated the impact of disruption on the SCN and the strategies for coping with the disruption risk. Mansory et al. [41] presented a model for evaluating suppliers and introduced some RPD criteria in the supply chain. Aliahmadi et al. [42] determined the impact factors on the intelligent and resilient SCN. In the field of designing SCN by RPD, each of the researchers has tried to design a resilient SCN by using policies. One of the primary studies in designing an SCN by RPD is related to the study of [43]. This study investigates the modeling approach for SCN design by RPD. In the following, researchers in the [44] developed the existing models and proposed a resilient network design model for the blood SCN. Rezapour et al. [45], Margolis et al. [46], and Hasani et al. [47] presented a model for SCN design by considering RPD, such as product holding, different suppliers, and raising capacity for factories. Hosseini-Motlagh et al. [48], Zahiri et al. [49], and Mohammed et al. [50] designed a resilient-sustainable SCN. Also, capacity planning for network design considering RPD and sustainability is addressed by Sazvar et al. [51]. Lotfi et al. [52] presented a two-stage mixed integer linear programming model for designing the closed-loop SCN of the machine assembly by RPD in Iran. In the paper published by Vali-Siar and Roghanian [22], the role of different RPD in reducing SCN costs is evaluated. Philsoophian et al. [53] categorized the proposed RPD models and presented a review article. Tordecilla et al. [54] reviewed the optimization and simulation methods for designing and evaluating the SCN under uncertainty. Also, other authors, such as Ivanov and Dolgui [55] and

Hosseini et al. [56], have reviewed the related work in this field.

Table 1 shows the most critical works on this issue. The related works show that quantitative models related to AS require more attention. Considering the responsiveness time and RPD in the SCN and examining the role of each of these concepts in network design have been rarely addressed in the literature. The introduction of time, considering the methods of meeting the customer needs promptly, and evaluating the connection of AS require more attention from researchers in this field. Investigating the impact of each AS by asset type and AS levels on the delivery time has been less seen in related works. Appling responsiveness strategies such as responsiveness level, lead-time, and LS in the mathematical models are rarely addressed.

Table 1. The abstract of the literature.

	Input									Direction		Output						Type of AS			
References	**INR**	**BMR**	**OSR**	**Shipping Cost**	**Holding Cost**	**Processing Cost**	**Establishment Cost**	**AS Cost**	**Time**	**Forward**	**Backward**	**Amount of Product**	**Optimal Route**	**Cooperator Selection**	**Shipment Direction**	**Optimal Places**	**Production Methods**	**Horizontally**	**Vertically**	**Hybrid**	**RPD**
[25]				✓	✓	✓				✓		✓						✓			
[26]			✓	✓						✓		✓						✓			
[27]			✓	✓						✓		✓				✓		✓			
[15]	✓			✓		✓	✓		✓	✓	✓				✓	✓					
[27]			✓	✓	✓	✓						✓				✓		✓			
[38]				✓		✓				✓					✓	✓		✓			
[30]			✓	✓		✓	✓			✓		✓	✓		✓	✓		✓			
[32]				✓		✓	✓			✓					✓	✓		✓			
[33]				✓			✓	✓		✓				✓	✓	✓		✓			
[18]	✓		✓	✓		✓	✓		✓	✓					✓	✓					✓
[31]			✓	✓		✓	✓			✓	✓	✓	✓		✓	✓		✓			
[52]	✓		✓	✓			✓			✓	✓				✓	✓					✓
[47]	✓		✓	✓		✓	✓			✓					✓	✓					✓
[51]	✓		✓	✓	✓	✓	✓		✓	✓					✓	✓					✓
[22]	✓		✓	✓		✓	✓			✓	✓				✓	✓	✓				✓
[35]				✓	✓	✓				✓					✓			✓			
[36]			✓							✓		✓			✓	✓		✓			
[34]			✓	✓		✓	✓			✓					✓	✓		✓			✓
This study	✓	✓		✓		✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓			✓

INR: Inside of SSC Risks BMR: Between Members of SSC Risks OSR: Outside SSC Risks

In this article, a model is presented that uses AS to deal with technological risks, as well as increase responsiveness in the SCN design. Responsiveness strategies such as responsiveness deviation and LS are addressed. Also, in this research, AS and RP are considered two policies to deal with the risk and to increase resiliency and responsiveness. In this study, the production time is uncertain due to technological risks and equipment failure, and an objective function has been presented for responsiveness. In addition, there is a penalty for unmeeting the demand for increasing customer satisfaction in the objective function. Due to uncertainty risks such as a change in capacity reduction and product production time, a new stochastic optimization method based on Aghezzaf et al. [57] has been used to deal with these risks. Due to the MO, an augmented ε-constraint way has been localized and developed. So, the novelty of the study can be described as follows:

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- *Examining the role of AS in improving responsiveness in multi-echelon SSC.*
- *Appling responsiveness deviation and LS in the mathematical modeling under uncertainty.*
- *Applying new stochastic optimization based on scenarios to cope with uncertainty.*
- *Considering the time to deliver the product and penalty cost for unsatisfied customers in the mathematical model.*
- *Localization and development of an augmented ε-constraint method to solve the MO model.*

3 | Problem Definition and Model Formulations

The network used in this study is in the metal production industries. They engage in joint production by sharing their assets, such as equipment, repair capabilities, expert workforce, and other production assets. Next, the resulting product is sent to metal-producing factories. In these factories, the shape of the crude product must be altered, and the final product must be produced. Like steel factories, there will be a possibility of AS and joint production in these factories, and then the manufactured product will be available to the distributors. Due to the probability of losing the capacity of the distributors, it is possible that due to the AS, the required product will be shared and transferred from the Reliable Distributor (RD) to the Unreliable Distributor (UD), and the customer's demand will be met. These products can be collected again after distribution among the customers by Collection Centers (CC), for which a percentage has been predicted. Finally, these products are moved to steel factories and used to produce new products. *Fig. 1* depicts the provided explanation. Considered assumptions are as follows:

- *The possibility of disaster is considered with the help of different scenarios in the modeling.*
- *The possibility of AS between facilities has been seen in steel and metal-producing factories.*
- *LS and AS have been used to increase responsiveness in disruption on the SSC.*
- *It is assumed that AS is used to increase the speed of responsiveness after the occurrence of risks related to equipment failure.*
- *The maximum deviation allowed at the delivery time of products is already known.*
- *Due to the possibility of technological risk, the production time of the products is considered uncertain.*

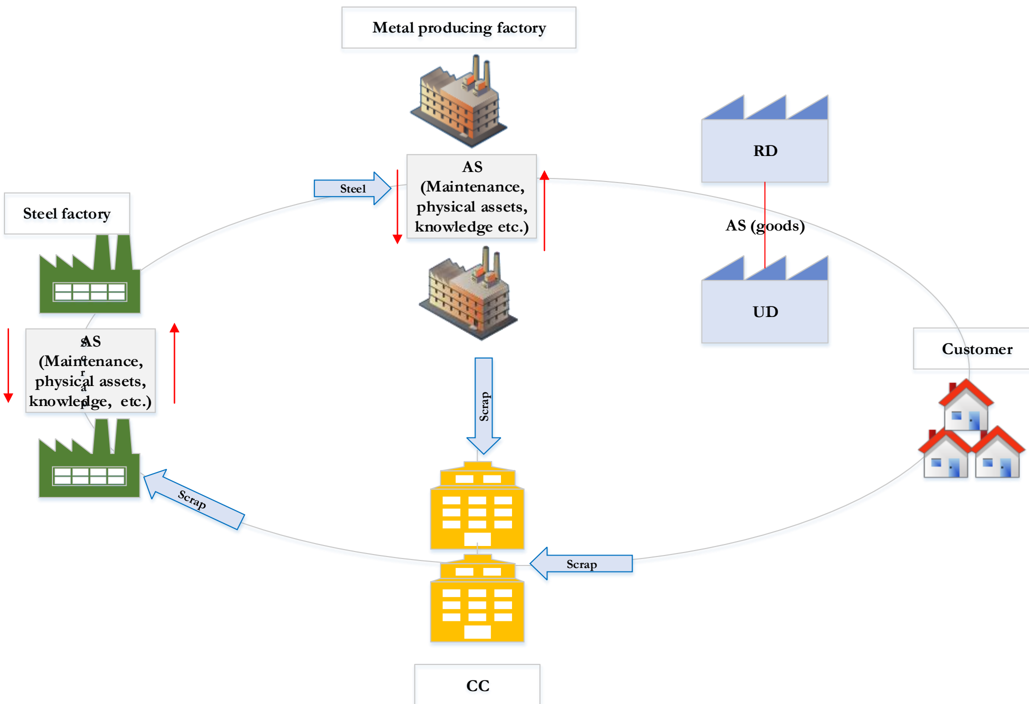

Fig. 1. Flow of product in the SSC.

3.1 | Proposing Model under Uncertainty

Considering the uncertainty in some parameters, we used scenario building for uncertain parameters and the robust optimization method provided by Aghezzaf et al. [57]. This method takes into account the lost sales for different scenarios. Also, the maximum deviations are minimized in this model, providing better answers than the deterministic model. The notification considered in the model is as follows:

Indexes

o: Index for the steel factories.

p: Index for metal-producing factories.

c: Index for capacities in steel factories.

t: Index for CC.

q: Index for production method in steel factories.

m: Index for RD.

n: Index for UD.

r: Index for a customer.

f: Index for RP level.

g: Index for AS part in steel factories.

h: Index for AS part in metal-producing factories.

k: Index for the number of steel factories that have AS.

l: Index for the amount of metal-producing factories that have AS.

s: Index for scenarios.

Parameters

Eo_{of}^{cq}: Establishment cost of steel factory o, with production method q, RP part f, and capacity c.

Em_m: Establishment cost of RD m.

En_n: Establishment cost of UD n.

Et_t^f: Establishment cost of collection center t with RP part f.

Vo_{og}^{cq}: Allowable valency of factory o with production method q AS part g, and capacity c.

Vp_p: Allowable valency of factory p.

Vm_m: Allowable valency of RD m.

Vn_n: Allowable valency of UD n.

Vt_t: Allowable valency of collection center t.

π_{ab}: Distance of location a to b.

$o\rho_{og}^{cq}$: Operating cost in factory o with production method q, AS part g, and capacity c.

$p\rho_p^h$: Operating cost in factory p with AS part h.

$m\rho_m$: Processing cost in RD m.

$n\rho_n$: Processing cost in UD n.

$t\rho_t$: Processing cost in the CC t.

$\varnothing$: Transporting cost per distance per ton.

rw_p: Percentage of waste in factory p.

dr_r^s: Customer demand r in scenario s

sr_r^s: Percentage of returned scraps in customer r in scenario s.

β: Capacity of sending among factories or distributors.

ti: Shiping time per ton of metal product per distance.

to_{og}^{fs}: Production time each ton in factory o with RP part f and AS part g in scenario s.

tp_{ph}^s: Production time each ton in factory p with AS part h in scenario s.

tm_m^s: Handling time each ton in RD m in scenario s.

tn_n^s: Handling time each ton in UD n in scenario s.

tt_t^{fs}: Collecting and inspecting time each ton in CC t with RP part f in scenario s.

fo_{og}^{fs}: Rate of disrupted capacity in factory o with RP part f and AS part g in scenario s.

fp_{ph}^s: Rate of disrupted capacity in factory b with AS part h in scenario s.

fm_m^s: Rate of disrupted capacity in RD m in scenario s.

fn_n^s: Rate of disrupted capacity in UD n in scenario s.

ft_t^{fs}: Rate of disrupted capacity in CC t with RP part f in scenario s.

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ro_{max}: The maximum adverse event in AS between steel factories.

ro_{min}: The minimum adverse event in AS between steel factories.

rp_{max}: The maximum adverse event in AS between metal-producing factories.

rp_{min}: The minimum adverse event in AS between metal-producing factories.

$Aeo_{oo'}$: The possible adverse event in AS between steel factories.

$Aep_{pp'}$: The possible adverse event in AS between metal-producing factories.

$lo\ (g)$: The minor acceptable limit for AS part g.

$lp\ (h)$: The minor acceptable limit for AS part h.

$uo\ (g)$: The high acceptable limit for AS part g.

$up\ (h)$: The high acceptable limit for AS part h.

co_o^k: Cost of AS between plants o and k other plants.

cp_p^l: Cost of AS between plants o and k other plants.

α: Maximum acceptable for deviation of responsiveness in SSC.

ph_s: Possibility of scenario s.

ω_1, ω_2: The average weight in the Aghezzaf method.

θ_1, θ_2: The deviations weight in the Aghezzaf method.

Ω_1, Ω_2: Penalty cost for unsatisfied customer demand.

$\gamma_{1s}^*, \gamma_{2s}^*$: Optimal value in goals for each scenario.

Decision variables

u_{ofg}^{qc}: Binary variable one if factory o with production method q, RP part f, AS part g, and capacity c is opened; zero otherwise.

v_m: Binary variable one if RD m is opened; zero otherwise.

z_n: Binary variable one if UD n is opened; zero otherwise.

y_t^f: Binary variable one if CC t with RP part f is opened; zero otherwise.

$ko_{oo'}$: Binary variable one if factory o has AS with factory o′; zero otherwise.

$kp_{pp'}$: Binary variable one if factory p has AS with factory p′; zero otherwise.

no_o^k: Binary variable one if the number of factories with AS with factory o is k; otherwise, zero.

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np_p^l: Binary variable one if the number of factories with AS with factory p is l; otherwise, zero.

ao_o^g: Binary variable one if factory o is given to part g; zero otherwise.

ap_p^h: Binary variable one if factory p is given to part h; zero otherwise.

$o\varphi_o^s$: The volume of returned products in the factories under scenario s.

$p\varphi_{ogp}^{qcs}$: The volume of steel sent from factory o with capacity c, production method q, and AS part g, to factory p under scenario s.

$m\varphi_{pm}^{hs}$: The volume sent from factory p with AS part h to the RD m in scenario s.

$n\varphi_{pn}^{hs}$: The volume sent from factory p with AS part h to UD n in scenario s.

$r\varphi_{mr}^s$: The volume sent from RD m to customer r in scenario s.

$b\varphi_{nr}^s$: The volume sent from UD n to customer r in scenario s.

$a\varphi_{mn}^s$: The volume sent from RD m to UD n in disruption in scenario s.

$d\varphi_{rt}^s$: The volume sent from the customer r to the CC t in scenario s.

$t\varphi_{to}^s$: The volume sent from the collection center t to the factory o in scenario s.

$c\varphi_{pt}^{hs}$: The volume sent from the factory p with AS part h to the collection center t in scenario s.

μ_1^{sr}, μ_2^{sr}: The volume of lost sales and not collecting scrap in customer r under scenario s.

The objective function and constraint in the robust optimization method provided by Aghezzaf et al. [57] are as follows:

$$\mathrm{w} = \omega \sum_{\mathrm{s}} \mathrm{ph_s}(\gamma_{\mathrm{s}}) + \theta \mathrm{Max}(\gamma_{\mathrm{s}} - \gamma_{\mathrm{s}}^*), \tag{1}$$

$$\mathrm{Max}(\gamma_{\mathrm{s}} - \gamma_{\mathrm{s}}^*) \geq (\gamma_{\mathrm{s}} - \gamma_{\mathrm{s}}^*) \quad \text{for all s.} \tag{2}$$

In *Eq. (1)*, in the first part, the average and in the second part, the maximum deviation is minimized. *Eq. (2)* shows the deviation among the scenarios and is added in constraints. So, the final model is as follows:

$$
\begin{aligned}
\text{Min } w_1 = {} & \sum_{o}\sum_{f}\sum_{c}\sum_{q}\sum_{m} Eo_{of}^{cq} u_{ofg}^{qc} + \sum_{m} Em_m v_m + \sum_{n} En_n z_n \\
& + \sum_{t}\sum_{f} Et_t^f y_t^f + \sum_{k}\sum_{o} no_o^k co_o^k + \sum_{p}\sum_{l} np_p^l cp_p^l \\
& + \omega_1 \sum_{s} ph_s\Big(\sum_{o}\sum_{g}\sum_{p}\sum_{q}\sum_{c} p\varphi_{ogp}^{qcs} \left(\pi_{op}\emptyset + o\rho_{og}^{cq}\right) \\
& + \sum_{p}\sum_{m}\sum_{h} \left(\pi_{pm}\emptyset + p\rho_p^h\right) m\varphi_{pm}^{hs} \\
& + \sum_{p}\sum_{n}\sum_{h} \left(\pi_{pn}\emptyset + p\rho_p^h\right) n\varphi_{pn}^{hs} \\
& + \sum_{p}\sum_{t}\sum_{h} \left(\pi_{pt}\emptyset + p\rho_p^h\right) c\varphi_{pt}^{hs} + \sum_{m}\sum_{r} \left(\pi_{mr}\emptyset + m\rho_m\right) r\varphi_{mr}^{s} \\
& + \sum_{n}\sum_{r} \left(\pi_{nr}\emptyset + n\rho_n\right) b\varphi_{nr}^{s} + \sum_{m}\sum_{n} \left(\pi_{mn}\emptyset + m\rho_m\right) a\varphi_{mn}^{s} \\
& + \sum_{r}\sum_{t} \pi_{rt}\emptyset\, d\varphi_{rt}^{s} + \sum_{t}\sum_{o} \left(\pi_{to}\emptyset + t\rho_t\right) t\varphi_{to}^{s}\Big) \\
& + \theta_1 \text{Max}\Bigg[\sum_{o}\sum_{g}\sum_{p}\sum_{q}\sum_{c} p\varphi_{ogp}^{qcs} \left(\pi_{op}\emptyset + o\rho_{og}^{cq}\right) \\
& + \sum_{p}\sum_{m}\sum_{h} \left(\pi_{pm}\emptyset + p\rho_p^h\right) m\varphi_{pm}^{hs} \\
& + \sum_{p}\sum_{n}\sum_{h} \left(\pi_{pn}\emptyset + p\rho_p^h\right) n\varphi_{pn}^{hs} \\
& + \sum_{p}\sum_{t}\sum_{h} \left(\pi_{pt}\emptyset + p\rho_p^h\right) c\varphi_{pt}^{hs} + \sum_{m}\sum_{r} \left(\pi_{mr}\emptyset + m\rho_m\right) r\varphi_{mr}^{s} \\
& + \sum_{n}\sum_{r} \left(\pi_{nr}\emptyset + n\rho_n\right) b\varphi_{nr}^{s} + \sum_{m}\sum_{n} \left(\pi_{mn}\emptyset + m\rho_m\right) a\varphi_{mn}^{s} \\
& + \sum_{r}\sum_{t} \pi_{rt}\emptyset\, d\varphi_{rt}^{s} + \sum_{t}\sum_{o} \left(\pi_{to}\emptyset + t\rho_t\right) t\varphi_{to}^{s}\Big) - \gamma_{1s}^{*} \Bigg] \\
& + \Omega_1 \sum_{s}\sum_{r} ph_s\, \mu_1^{sr} + \Omega_2 \sum_{s}\sum_{r} ph_s\, \mu_2^{sr},
\end{aligned}
\tag{3}
$$

$$
\begin{aligned}
\text{Min } w_2 = {} & \omega_2 \sum_{s} ph_s\Big(\sum_{o}\sum_{g}\sum_{p}\sum_{q}\sum_{c}\sum_{f} \left(to_{og}^{fs} + \pi_{op} * \frac{ti}{\beta}\right) p\varphi_{ogp}^{qcs} \\
& + \sum_{p}\sum_{m}\sum_{h} \left(tp_{ph}^{s} + \pi_{pm} * \frac{ti}{\beta}\right) m\varphi_{pm}^{hs} \\
& + \sum_{p}\sum_{n}\sum_{h} \left(tp_{ph}^{s} + \pi_{pn} * \frac{ti}{\beta}\right) n\varphi_{pn}^{hs} \\
& + \sum_{p}\sum_{t}\sum_{h} \left(tp_{ph}^{s} + \pi_{pt} * \frac{ti}{\beta}\right) c\varphi_{pt}^{hs} + \sum_{n}\sum_{r} \left(tn_{n}^{s} + \pi_{nr} * \frac{ti}{\beta}\right) b\varphi_{nr}^{s} \\
& + \sum_{m}\sum_{r} \left(tm_{m}^{s} + \pi_{mr} * \frac{ti}{\beta}\right) r\varphi_{mr}^{s} + \sum_{m}\sum_{n} \left(tm_{m}^{s} + \pi_{mn} * \frac{ti}{\beta}\right) a\varphi_{mn}^{s} \\
& + \sum_{r}\sum_{t} \left(\pi_{rt} * \frac{ti}{\beta}\right) d\varphi_{rt}^{s} + \sum_{t}\sum_{o}\sum_{f} \left(tt_{t}^{fs} + \pi_{to} * \frac{ti}{\beta}\right) t\varphi_{to}^{s}\Big) \\
& + \theta_2 \text{Max}\Big[\Big(\sum_{o}\sum_{g}\sum_{p}\sum_{q}\sum_{c}\sum_{f} \left(to_{og}^{fs} + \pi_{op} * \frac{ti}{\beta}\right) p\varphi_{ogp}^{qcs}
\end{aligned}
\tag{4}
$$

$$+\sum_{p}\sum_{m}\sum_{h}(tp_{ph}^{s}+\pi_{pm}*\frac{ti}{\beta})m\varphi_{pm}^{hs}+\sum_{p}\sum_{n}\sum_{h}(tp_{ph}^{s}+\pi_{pn}*\frac{ti}{\beta})n\varphi_{pn}^{hs}$$
$$+\sum_{p}\sum_{t}\sum_{h}(tp_{ph}^{s}+\pi_{pt}*\frac{ti}{\beta})c\varphi_{pt}^{hs}+\sum_{n}\sum_{r}(tn_{n}^{s}+\pi_{nr}*\frac{ti}{\beta})b\varphi_{nr}^{s}$$
$$+\sum_{m}\sum_{r}(tm_{m}^{s}+\pi_{mr}*\frac{ti}{\beta})r\varphi_{mr}^{s}+\sum_{m}\sum_{n}(tm_{m}^{s}+\pi_{mn}*\frac{ti}{\beta})a\varphi_{mn}^{s}$$
$$+\sum_{r}\sum_{t}(\pi_{rt}*\frac{ti}{\beta})d\varphi_{rt}^{s}+\sum_{t}\sum_{o}\sum_{f}(tt_{t}^{fs}+\pi_{to}*\frac{ti}{\beta})t\varphi_{to}^{s})-\gamma_{2s}^{*}],$$

$$\text{Min } w_3 = wo\left(\sum_{o\,(o\neq o')}\sum_{o'}Aeo_{oo'}\,ko_{oo'}-ro_{min}\right)\frac{1}{ro_{max}-ro_{min}}$$
$$+wp\left(\sum_{p\,(p\neq p')}\sum_{p'}Aep_{pp'}\,kp_{pp'}-rp_{min}\right)\frac{1}{rp_{max}-rp_{min}}, \tag{5}$$

$$\sum_{o'\,(o\neq o')} ko_{oo'} = \sum_{k} k*no_{o}^{k} \quad \text{for all } o, \tag{6}$$

$$\sum_{p'\,(p\neq p')} kp_{pp'} = \sum_{l} l*np_{p}^{l} \quad \text{for all } p, \tag{7}$$

$$\sum_{g} ao_{o}^{g} \leq 1 \quad \text{for all } o, \tag{8}$$

$$\sum_{h} ap_{p}^{h} \leq 1 \quad \text{for all } p, \tag{9}$$

$$\sum_{g} ao_{o}^{g} \leq \sum_{l} no_{o}^{k} \quad \text{for all } o, \tag{10}$$

$$\sum_{h} ap_{p}^{h} \leq \sum_{l} np_{p}^{l} \quad \text{for all } p, \tag{11}$$

$$\sum_{g} lo(g)ao_{o}^{g} \leq \sum_{k} k*no_{o}^{k} \quad \text{for all } o, \tag{12}$$

$$\sum_{k} k*no_{o}^{k} \leq \sum_{g} uo(g)ao_{o}^{g} \quad \text{for all } o, \tag{13}$$

$$\sum_{h} lp(h)ap_{p}^{h} \leq \sum_{l} l*np_{p}^{l} \quad \text{for all } p, \tag{14}$$

$$\sum_{l} l*np_{p}^{l} \leq \sum_{h} up(h)ap_{p}^{h} \quad \text{for all } p, \tag{15}$$

$$ko_{oo'}+ko_{o'o''}-ko_{oo''} \leq 1 \quad \text{for all } o, \tag{16}$$

$$ko_{pp'}+ko_{p'p''}-ko_{pp''} \leq 1 \quad \text{for all } p, \tag{17}$$

$$\sum_{f}\sum_{q}\sum_{c}\sum_{g} u_{ofg}^{qc} \geq \sum_{g} ao_{o}^{g} \quad \text{for all } o, \tag{18}$$

$$u_{ofg}^{qc} \leq ao_{o}^{g} \quad \text{for all } o,f,g,q,c, \tag{19}$$

$$\sum_{p} p\varphi_{ogp}^{qcs} \leq Vo_{og}^{cq}\sum_{f} u_{ofg}^{qc}\left(1-fo_{og}^{fs}\right) \quad \text{for all } o,g,c,q,s, \tag{20}$$

$$\sum_{p}\sum_{h} m\varphi_{pm}^{hs} \leq Vm_{m}v_{m}(1-fm_{m}^{s}) \quad \text{for all } m,s, \tag{21}$$

$$\sum_{p}\sum_{h} n\varphi_{pn}^{hs} \leq Vn_{n}z_{n}(1-fn_{n}^{s}) \quad \text{for all } n,s, \tag{22}$$

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$$\sum_{m} a\varphi^{s}_{mn} \leq Vn_n z_n fn^{s}_{n} \quad \text{for all } n, s, \tag{23}$$

$$\sum_{o} t\varphi^{s}_{to} \leq Vt_t \sum_{f} y^{f}_{t}\left(1 - ft^{fs}_{t}\right) \quad \text{for all } t, s, \tag{24}$$

$$\sum_{m} m\varphi^{hs}_{pm} + \sum_{n} n\varphi^{hs}_{pn} + \sum_{t} c\varphi^{hs}_{pt} \leq ap^{h}_{p} Vp_p \left(1 - fp^{s}_{ph}\right) \quad \text{for all } p, h, s, \tag{25}$$

$$\sum_{m} v_m \geq 1 \quad \text{for all } m, \tag{26}$$

$$\sum_{f}\sum_{q}\sum_{c}\sum_{g} u^{qc}_{ofg} = 1 \quad \text{for all } o, \tag{27}$$

$$\sum_{p}\sum_{h} m\varphi^{hs}_{pm} = \sum_{r} r\varphi^{s}_{mr} + \sum_{n} a\varphi^{s}_{mn} \quad \text{for all } m, s, \tag{28}$$

$$\sum_{p}\sum_{h} n\varphi^{hs}_{pn} + \sum_{m} a\varphi^{s}_{mn} = \sum_{r} b\varphi^{s}_{nr} \quad \text{for all } n, s, \tag{29}$$

$$rw_p \sum_{o}\sum_{g}\sum_{q}\sum_{c} p\varphi^{qcs}_{ogp} = \sum_{h}\sum_{t} c\varphi^{hs}_{pt} \quad \text{for all } p, s, \tag{30}$$

$$\left(1 - rw_p\right) \sum_{o}\sum_{g}\sum_{q}\sum_{c} p\varphi^{qcs}_{ogp} = \sum_{h}\sum_{m} m\varphi^{hs}_{pm} + \sum_{h}\sum_{n} n\varphi^{hs}_{pn} \quad \text{for all } p, s, \tag{31}$$

$$\sum_{o} t\varphi^{s}_{to} + o\varphi^{s}_{o} = \sum_{g}\sum_{q}\sum_{c}\sum_{p} p\varphi^{qcs}_{ogp} \quad \text{for all } o, s, \tag{32}$$

$$\sum_{o} t\varphi^{s}_{to} = \sum_{p}\sum_{h} c\varphi^{hs}_{pt} + \sum_{r} d\varphi^{s}_{rt} \quad \text{for all } t, s, \tag{33}$$

$$\sum_{m} r\varphi^{s}_{mr} + \sum_{n} b\varphi^{s}_{nr} + \mu^{sr}_{1} = dr^{s}_{r} \quad \text{for all } r, s, \tag{34}$$

$$\sum_{t} d\varphi^{s}_{rt} + \mu^{sr}_{2} = \left(\sum_{m} r\varphi^{s}_{mr} + \sum_{n} b\varphi^{s}_{nr}\right) * sr^{s}_{r} \quad \text{for all } r, s, \tag{35}$$

$$\begin{aligned}
&\text{Max}\Big[\textstyle\sum_o \sum_g \sum_p \sum_q \sum_c p\varphi^{qcs}_{ogp} \left(\pi_{op}\emptyset + o\rho^{cq}_{og}\right) + \sum_p \sum_m \sum_h \left(\pi_{pm}\emptyset + p\rho^{h}_{p}\right) m\varphi^{hs}_{pm} + \\
&\textstyle\sum_p \sum_n \sum_h \left(\pi_{pn}\emptyset + p\rho^{h}_{p}\right) n\varphi^{hs}_{pn} + \sum_p \sum_t \sum_h \left(\pi_{pt}\emptyset + p\rho^{h}_{p}\right) c\varphi^{hs}_{pt} + \sum_m \sum_r (\pi_{mr}\emptyset + \\
&m\rho_m) r\varphi^{s}_{mr} + \textstyle\sum_n \sum_r (\pi_{nr}\emptyset + n\rho_n) b\varphi^{s}_{nr} + \sum_m \sum_n (\pi_{mn}\emptyset + m\rho_m) a\varphi^{s}_{mn} + \\
&\textstyle\sum_r \sum_t \pi_{rt}\emptyset\, d\varphi^{s}_{rt} + \sum_t \sum_o (\pi_{to}\emptyset + t\rho_t) t\varphi^{s}_{to}) - \gamma^{*}_{1s}\Big] \geq \Big[\sum_o \sum_g \sum_p \sum_q \sum_c p\varphi^{qcs}_{ogp} \big(\pi_{op}\emptyset + \\
&o\rho^{cq}_{og}\big) + \textstyle\sum_p \sum_m \sum_h \left(\pi_{pm}\emptyset + p\rho^{h}_{p}\right) m\varphi^{hs}_{pm} + \sum_p \sum_n \sum_h \left(\pi_{pn}\emptyset + p\rho^{h}_{p}\right) n\varphi^{hs}_{pn} + \\
&\textstyle\sum_p \sum_t \sum_h \left(\pi_{pt}\emptyset + p\rho^{h}_{p}\right) c\varphi^{hs}_{pt} + \sum_m \sum_r (\pi_{mr}\emptyset + m\rho_m) r\varphi^{s}_{mr} + \sum_n \sum_r (\pi_{nr}\emptyset + n\rho_n) b\varphi^{s}_{nr} + \\
&\textstyle\sum_m \sum_n (\pi_{mn}\emptyset + m\rho_m) a\varphi^{s}_{mn} + \sum_r \sum_t \pi_{rt}\emptyset\, d\varphi^{s}_{rt} + \sum_t \sum_o (\pi_{to}\emptyset + t\rho_t) t\varphi^{s}_{to}) - \gamma^{*}_{1s}\Big]
\end{aligned} \tag{36}$$

$$\begin{aligned}
&\text{Max}[(\textstyle\sum_o \sum_g \sum_p \sum_q \sum_c \sum_f (to^{fs}_{og} + \pi_{op} * \frac{ti}{\beta}) p\varphi^{qcs}_{ogp} + \sum_p \sum_m \sum_h (tp^{s}_{ph} + \pi_{pm} * \\
&\tfrac{ti}{\beta}) m\varphi^{hs}_{pm} + \textstyle\sum_p \sum_n \sum_h (tp^{s}_{ph} + \pi_{pn} * \frac{ti}{\beta}) n\varphi^{hs}_{pn} + \sum_p \sum_t \sum_h (tp^{s}_{ph} + \pi_{pt} * \frac{ti}{\beta}) c\varphi^{hs}_{pt} + \\
&\textstyle\sum_n \sum_r (tn^{s}_{n} + \pi_{nr} * \frac{ti}{\beta}) b\varphi^{s}_{nr} + \sum_m \sum_r (tm^{s}_{m} + \pi_{mr} * \frac{ti}{\beta}) r\varphi^{s}_{mr} + \sum_m \sum_n (tm^{s}_{m} + \pi_{mn} * \\
&\tfrac{ti}{\beta}) a\varphi^{s}_{mn} + \textstyle\sum_r \sum_t (\pi_{rt} * \frac{ti}{\beta}) d\varphi^{s}_{rt} + \sum_t \sum_o \sum_f (tt^{fs}_{t} + \pi_{to} * \frac{ti}{\beta}) t\varphi^{s}_{to}) - \gamma^{*}_{2s}] \quad \geq \\
&[(\textstyle\sum_o \sum_g \sum_p \sum_q \sum_c \sum_f (to^{fs}_{og} + \pi_{op} * \frac{ti}{\beta}) p\varphi^{qcs}_{ogp} + \sum_p \sum_m \sum_h (tp^{s}_{ph} + \pi_{pm} * \frac{ti}{\beta}) m\varphi^{hs}_{pm} + \\
&\textstyle\sum_p \sum_n \sum_h (tp^{s}_{ph} + \pi_{pn} * \frac{ti}{\beta}) n\varphi^{hs}_{pn} + \sum_p \sum_t \sum_h (tp^{s}_{ph} + \pi_{pt} * \frac{ti}{\beta}) c\varphi^{hs}_{pt} + \sum_n \sum_r (tn^{s}_{n} + \pi_{nr} * \\
&\tfrac{ti}{\beta}) b\varphi^{s}_{nr} + \textstyle\sum_m \sum_r (tm^{s}_{m} + \pi_{mr} * \frac{ti}{\beta}) r\varphi^{s}_{mr} + \sum_m \sum_n (tm^{s}_{m} + \pi_{mn} * \frac{ti}{\beta}) a\varphi^{s}_{mn} + \sum_r \sum_t (\pi_{rt} * \\
&\tfrac{ti}{\beta}) d\varphi^{s}_{rt} + \textstyle\sum_t \sum_o \sum_f (tt^{fs}_{t} + \pi_{to} * \frac{ti}{\beta}) t\varphi^{s}_{to}) - \gamma^{*}_{2s}],
\end{aligned} \tag{37}$$

$$
\begin{aligned}
\mathrm{Max}[(&\sum_{o}\sum_{g}\sum_{p}\sum_{q}\sum_{c}\sum_{f}(to_{og}^{fs}+\pi_{op}*\frac{ti}{\beta})p\varphi_{ogp}^{qcs}\\
&+\sum_{p}\sum_{m}\sum_{h}(tp_{ph}^{s}+\pi_{pm}*\frac{ti}{\beta})m\varphi_{pm}^{hs}\\
&+\sum_{p}\sum_{n}\sum_{h}(tp_{ph}^{s}+\pi_{pn}*\frac{ti}{\beta})n\varphi_{pn}^{hs}\\
&+\sum_{p}\sum_{t}\sum_{h}(tp_{ph}^{s}+\pi_{pt}*\frac{ti}{\beta})c\varphi_{pt}^{hs}+\sum_{n}\sum_{r}(tn_{n}^{s}+\pi_{nr}*\frac{ti}{\beta})b\varphi_{nr}^{s}\\
&+\sum_{m}\sum_{r}(tm_{m}^{s}+\pi_{mr}*\frac{ti}{\beta})r\varphi_{mr}^{s}+\sum_{m}\sum_{n}(tm_{m}^{s}+\pi_{mn}*\frac{ti}{\beta})a\varphi_{mn}^{s}\\
&+\sum_{r}\sum_{t}(\pi_{rt}*\frac{ti}{\beta})d\varphi_{rt}^{s}+\sum_{t}\sum_{o}\sum_{f}(tt_{t}^{fs}+\pi_{to}*\frac{ti}{\beta})t\varphi_{to}^{s})-\gamma_{2s}^{*}],\\
\leq\ &\alpha.
\end{aligned}
\tag{38}
$$

$$
u_{ofg}^{qc}, v_m, z_n, y_t^f, ko_{oo'}, kp_{pp'}, ap_p^h, ao_o^g, no_o^k, np_p^l \in \{0,1\}, \tag{39}
$$

$$
p\varphi_{ogp}^{qcs}, m\varphi_{pm}^{hs}, n\varphi_{pn}^{hs}, c\varphi_{pt}^{hs}, t\varphi_{to}^{s} \geq 0. \tag{40}
$$

In *Eq. (3)*, expressions in brackets are related to maximum cost deviations, and the other remaining expressions are related to opening AS, lost sales, and average variable costs. In *Eq. (4)*, the expressions in brackets are the maximum time deviation, and the rest of the expressions are related to the average time of the network. In *Eq. (5)*, the number of undesirable events caused by AS in factories is minimized.

Eqs. (6) and *(7)* indicate the number of AS factories. *Eqs. (8)* and *(9)* state that a single AS part can be assigned to each factory. *Eqs. (10)* and *(11)* show the connection between the factories that have AS and their AS parts. In *Eqs. (12)* to *(15)*, the AS part in factories is determined based on the limits. *Eqs. (16)* and *(17)* show AS relation in producing factory. In *Eqs. (18)* and *(19)*, the link between the binary variable of factory creation and the variable of AS part is displayed. *Eqs. (20)* to *(25)* are the capacity controls. *Eq. (26)* specifies that the minimum number of the RD is one. *Eq. (27)* states that a steel factory with a single capacity, RP AS part, and production method can be opened in each place. *Eqs. (28)* to *(33)* exhibit the link between location and shipping variables. *Eqs. (34)* and *(35)* state the volume of steel conveyed to the customers and the amount of product to CC. *Eqs. (36)* and *(37)* determine the maximum deviation among all scenarios. *Eq. (38)* guarantees the maximum acceptable deviation of responsiveness in the SSC. *Eqs. (39)* and *(40)* show the applied variables in the models.

3.2 | Developing an Augmented Ɛ-Constraint Method

A new method is developed to solve the MO model. The way is based on Mavrotas [58], but some modifications have been made. This proposed method has some benefits; 1) this method does not change the dimensions of the model, 2) it will be easier to decide regarding the partial restriction amount, and 3) this method can be combined with other methods.

The solution stages in this method are as follows:

Step 1. Computing the best answers (w_j^{be}) for goal j, so other goals are ignored, and the proposed model with one objective considering the constraints of the mathematical model is resolved.

Step 2. Computing the worst answer (w_j^{wo}) for goal j in this stage. The worst answer is computed in the cost objective as follows:

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$$y_1^{wo} = \max\left(w_1\left(y_2^{be}\right), w_1\left(y_3^{be}\right)\right). \tag{41}$$

Step 3. To create an interval of zero and one for the easier choice of the decision maker, the desirability function is commuting for goals based on [59], which is as follows:

$$\xi_j(y) = \begin{cases} 1, & if \quad w_j < w_j^{be}, \\ \dfrac{w_j^{wo} - w_j}{w_j^{wo} - w_j^{be}}, & \text{if } \; w_j^{be} \le w_j \le w_j^{wo}, \\ 0, & \text{if } \; w_j > w_j^{wo}. \end{cases} \tag{42}$$

Step 4. Solving the MO model proposed by Mavrotas [58].

$$\begin{aligned} &\text{Max } \xi_j(y) + \varepsilon \sum_j \frac{su_j}{re_j}, \\ &\text{s.t.} \\ &\xi_j(y) - su_j = ep_j \quad \text{for all } j, \\ &ep_j \in \{0,1\}, su_j \ge 0. \end{aligned} \tag{43}$$

ep_j represents the minimum acceptable part of the objective function and is specified by the decision maker. The small number ε is between 10^{-3} and 10^{-6}, and re_j is the range of objective function j and is used for de-scaling [58].

According to [58], the presented model provides strong solutions. If the answer provided in the answer model is not strong, then there is another strong answer, which is as follows:

$$\begin{aligned} &ep_2 + su_2 \le ep_2 + su_2', \\ &ep_3 + su_3 \le ep_3 + su_3', \\ &ep_j + su_j \le ep_j + su_j'. \end{aligned} \tag{44}$$

It results that $\sum_j \frac{su_j}{re_j} \le \sum_j \frac{su_j'}{re_j}$ And Max $\xi_1(y) + \varepsilon \sum_j \frac{su_j}{re_j} \le$ Max $\xi_1(y) + \varepsilon \sum_j \frac{su_j'}{re_j}$.

This conflicts with the assumption of the maximum of the objective *Function (44)*, so the solution provided by the model is the dominant solution [58].

Step 5. Solve the model in stage four; if the result is acceptable, the algorithm is finished; otherwise, change the desired values and present a new answer to the decision maker.

4 | Case Study and Analysis of Results

Steel sectors and the production of metal products have a large share of the total industries in Iran. Since other sectors in the country, such as construction, railway sectors, production of auto spare parts, etc., are dependent on this industry, any increasing time in the production and distribution network of this product will cause damage to various producing sectors. Due to the dependence of other sectors on the SSC, the part of responsiveness and meeting customer demand is also high. To increase the productivity and efficiency of the SSC, AS in the maintenance field, the expert workforce, as well as production abilities and suitable production methods, can be an efficient solution. Therefore, we used data from an SSC in Iran as a case study in this study. *Fig. 2* shows the existing and potential places for opening the facilities. Also, *Table 2* displays the range of data used to implement the proposed model.

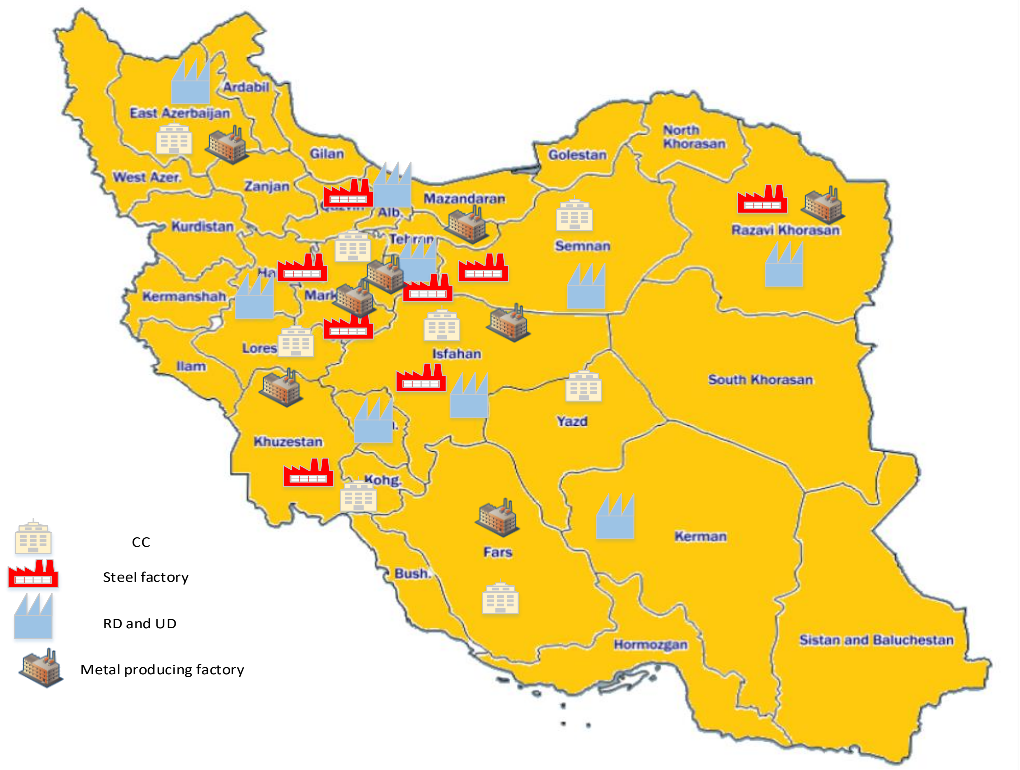

Fig. 2. Existing and potential places for opening the facilities.

Table 2. The data range used in the case study.

Factor	Bound	Factor	Bound
Eo_{of}^{1q}	U(295000،935000)	$do_{og}^{fs}, dp_{ph}^{s}, dt_{t}^{fs}, dn_{n}^{s}$	U(0،0.7)
Eo_{of}^{2q}	$\Upsilon \times Fo_{of}^{1q}$	$p\rho_{p}^{h}$	U(19،43)
Υ	U(0.55،0.75)	$m\rho_{m}$	U(1.5،4.5)
Em_{m}	U(5500،11500)	$n\rho_{n}$	U(3.5،8.5)
En_{n}	U(4100،8600)	$t\rho_{t}$	U(1.5،4.5)
Et_{t}^{f}	U(4100،8600)	sr_{r}^{s}	U(0.83،0.96)
Vo_{og}^{1q}	U(1300،3500)	ti	U(0.9،1.6)
Vo_{og}^{2q}	U(600،1850)	to_{og}^{fs}	U(0.55،0.95)
Vp_{p}	U(1280،3450)	tp_{ph}^{s}	U(0.4،0.85)
Vm_{m}, Vn_{n}, Vt_{t}	U(600،1850)	tm_{m}^{s}	U(0.05،0.27)
π_{ab}	U(8،1150)	tn_{n}^{s}	U(0.1،0.32)
op_{og}^{cq}	U(52،136)	tt_{t}^{fs}	U(0.05،0.27)

For implementing the model, GAMS and a computer with 6GB RAM and Intel(R) cori3-7100 specifications were used to run the model. In this article, the value of wo, wp= 0.5, is measured. Also, the ε value is considered to be 0.0001, according to Mavrotas [58]. In *Table 3*, the results for running the model with the augmented ε-constraint method are exhibited for different ep_j.

Table 3. Result of applying the MO solution method.

Row	Ep1	Ep2	Responsiveness Desirability	AS Risk Desirability	Cost Desirability	Total Cost
1	0.2	0	0.2	0	0.99	3175425
2	0.2	0.2	0.2	0.23	0.983	3174822
3	0.2	0.4	0.2	0.417	0.969	3196644
4	0.2	0.6	0.2	0.667	0.835	3304562
5	0.2	0.8	0.2	0.833	0.814	3321746

Table 3. Continued.

Row	Ep1	Ep2	Responsiveness Desirability	AS Risk Desirability	Cost Desirability	Total Cost
6	0.2	1	0.2	1	0.701	3412993
7	0.4	0	0.4	0	0.976	3190656
8	0.4	0.2	0.4	0.25	0.967	3194674
9	0.4	0.4	0.4	0.427	0.957	3205608
10	0.4	0.6	0.4	0.607	0.836	3304155
11	0.4	0.8	0.4	0.812	0.807	3327603
12	0.4	1	0.4	1	0.697	3416307
13	0.6	0	0.6	0	0.945	3215358
14	0.6	0	0.6	0.22	0.95	3211393
15	0.6	0.2	0.6	0.412	0.926	3230834
16	0.6	0.4	0.6	0.607	0.828	3310474
17	0.6	0.6	0.6	0.81	0.798	3334371
18	0.6	0.8	0.6	1	0.695	3417853
19	0.8	0	0.8	0	0.94	3219620
20	0.8	0.2	0.8	0.2	0.92	3235671
21	0.8	0.4	0.8	0.428	0.905	3247754
22	0.8	0.6	0.8	0.637	0.804	3329595
23	0.8	0.8	0.8	0.829	0.789	3341748
24	0.8	1	0.8	1	0.678	3441668

To analyze the performance of the model under uncertainty, the correlation between the cost of lost sales and the volume of lost sales, and the cost of the network is shown in *Fig. 3*. On the left, the network cost, on the right, total lost sales, on the horizontal axis, the penalty for lost sales is displayed, as shown in *Fig. 3* by rising the penalty of lost sales, the SCN costs rise and the amount of lost sales reductions. Also, *Fig. 3* shows that if the amount of lost sales has high costs, the SCN costs will also grow.

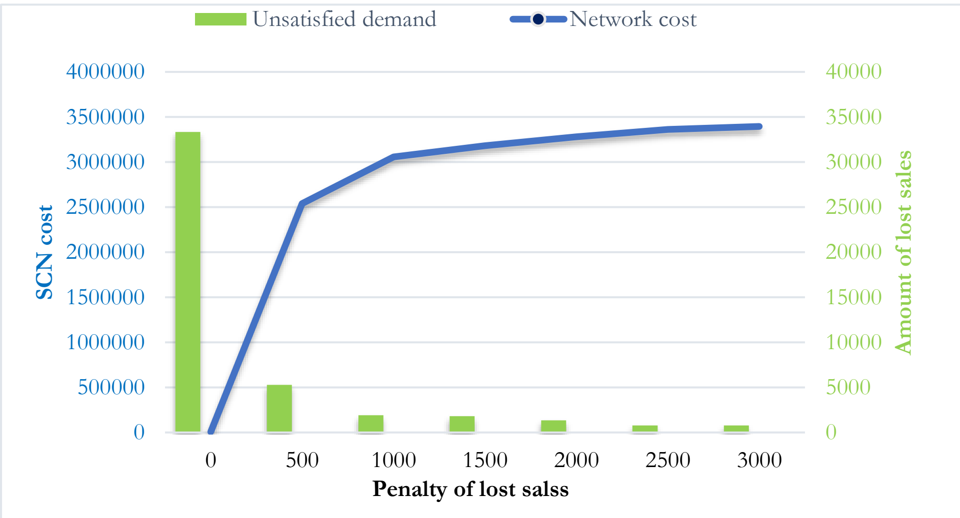

Fig. 3. Evaluation of costs and amount of lost sales with the penalty of lost sales.

In *Fig. 4*, the role of using RP, AS, and Ls in reducing the network cost has been calculated; as can be seen in *Fig. 4*, the RP, AS, and LS mitigate the SCN costs (11% for AS and 5% for RP and 4% for LS), and this reduction is higher in the AS and by using RP, AS, and LS, the SCN costs will decrease by 14%.

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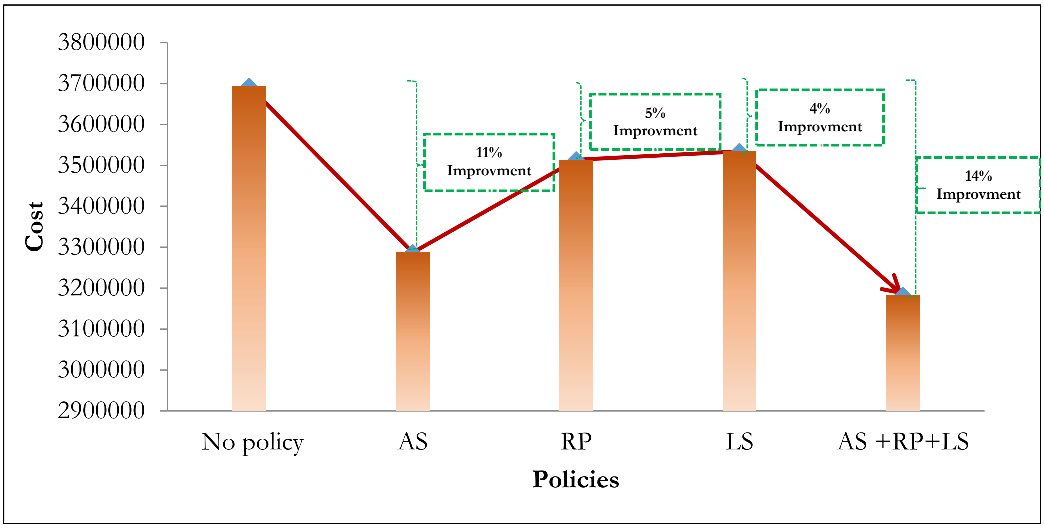

Fig. 4. The role of policies in cost reduction.

Also, for the responsiveness rate, the results show an increase in the desirability of the objective function by using an RP, AS, and LS. For example, this amount is 13% for AS, 7% for RP, and 4% for LS, and using RP, AS, and Ls simultaneously will bring up to 17% improvement in responsiveness (*Fig. 5*).

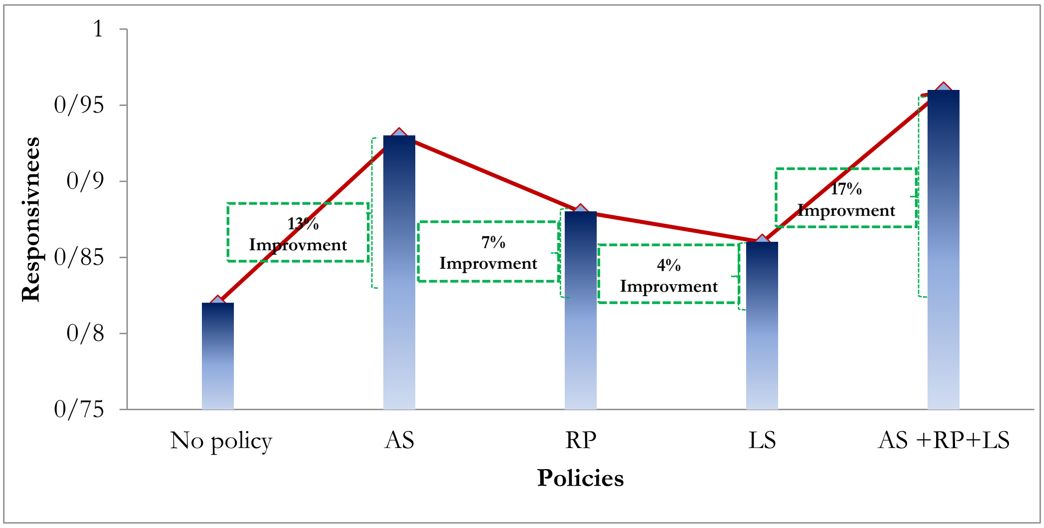

Fig. 5. The role of policies in decreasing time.

In *Fig. 6*, the relationship between the SCN cost and the AS risks is drawn, considering the responsiveness desirability of 0.5. As it is clear from *Fig. 6,* by reducing AS in the network, the risk part will decrease, and risk-desirability will increase, leading to a rise in SCN costs. In addition, the slope of the graph increases on the right side, which indicates a further height in SCN, costs to reach the part of desirability close to 1.

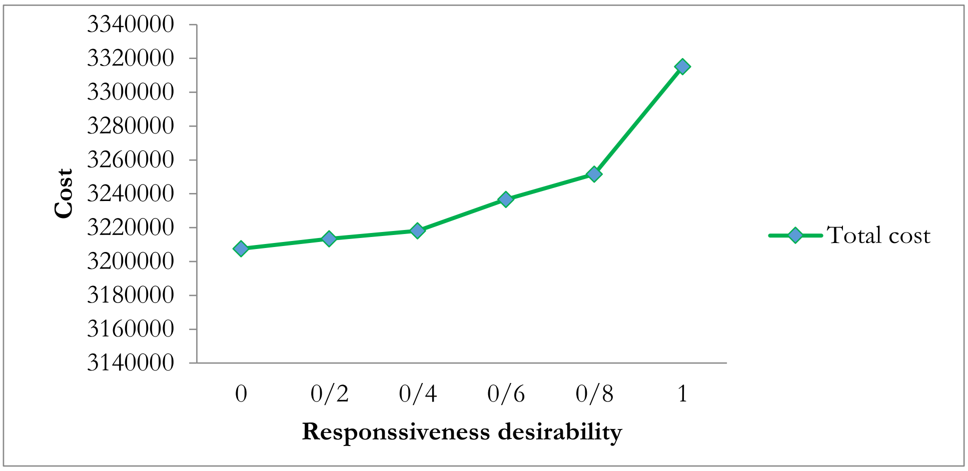

Fig. 6. Performance of cost vs. AS risk.

The relationship between responsiveness and total costs is also depicted in *Fig. 7*. As can be seen, increasing the desirability of responsiveness will increase the SCN cost, and the decision-makers, according to the degree of their desirability, can decide in this regard.

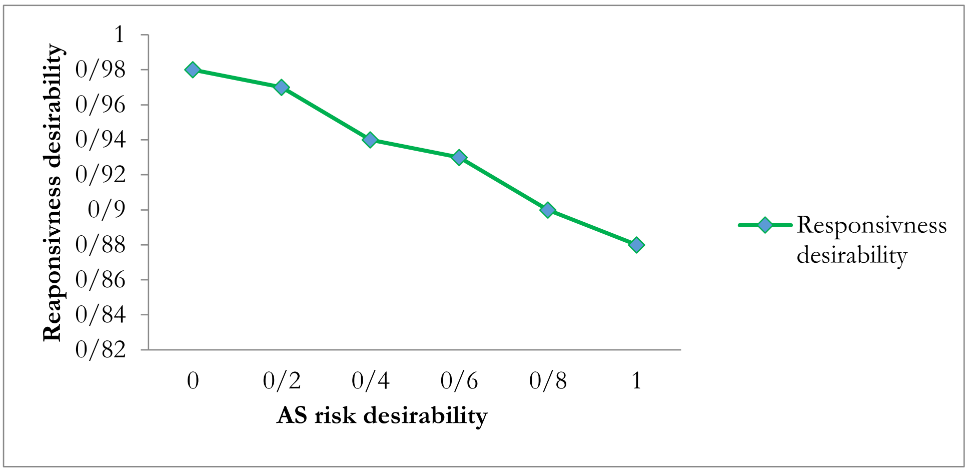

Fig. 7. Performance of cost vs. time.

Finally, the relationship between the second and third objective functions is shown in *Fig. 8*. As seen with the increase in the desirability of AS risks, the desirability of the responsiveness objective function decreases, indicating that the existence of the AS increases the level of responsiveness.

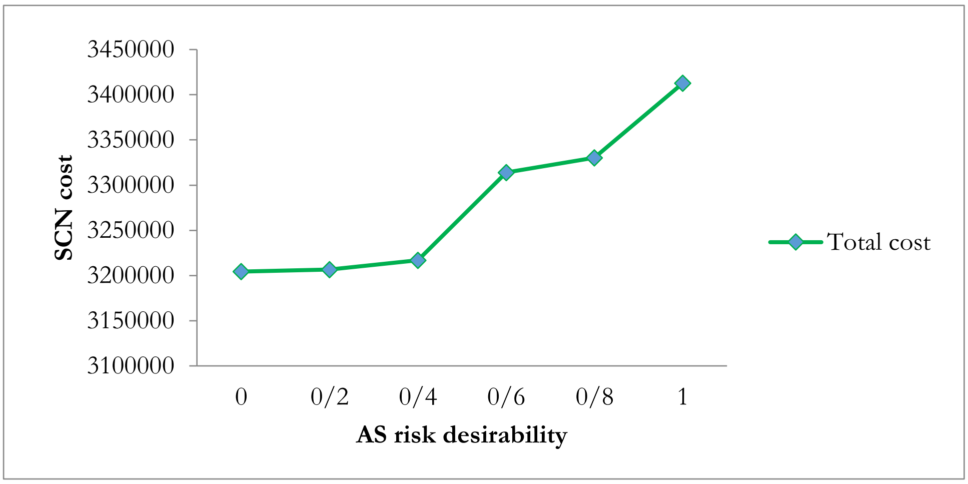

Fig. 8. Performance of time vs. AS risk.

4.1 | Practical Implications

I. Because using RP, AS, and Ls simultaneously will be beneficial in reducing SCN costs. Since the AS is more influential in reducing SCN costs than the RP, senior managers can focus on AS to decrease the total SSC cost.

II. Because in the presented model, the maximum amount allowed for the deviation of the delivery time can be changed if the delivery time of the products to the customers is essential. This case was considered in the model by allocating a smaller amount.

III. Since the simultaneous application of RP, AS, and LS can improve the response rate by up to 17% in cases where the part of competitiveness between different supply chains is high, the use of the mentioned policies has a valuable role in increasing customer satisfaction and company fame because increasing the response rate will increase customer loyalty and, as a result, increase the profit of the chain.

IV. In this article, LS was evaluated. If LS is possible, this strategy can play an influential role in increasing responsiveness in the SCN.

V. Due to the uncertainty in the various input parameters to the mathematical model, the presented model can play an influential role in reducing the SCN costs because, in this model, there is the ability to observe the maximum deviation of the costs in the future. For this reason, senior managers can reduce their investment risk in the future by using the model under uncertainty.

VI. Metal production is done with the help of collected scraps, and the greater availability of these scraps plays an influential role in reducing SCN costs. System managers can allocate more penalties for the non-collection product. So, collecting returned products will increase the amount of scrap entering the network and help the profitability of the SCN.

VII. Creating scenarios and predicting the probability of each scenario more accurately can reduce the cost deviation in the future. For this purpose, using software, data available in the industry, such as data extracted from physics asset management software, play a constructive role in this case.

VIII. Since the research results show the increase in network efficiency with AS and this AS will also bring risks, steel SCN senior managers can use solutions with less risk, for example, equipment sharing, to monitor the condition of the equipment that improves network performance with less risk.

5 | Concluding Remarks and Future Suggestions

In recent decades, senior managers have paid particular attention to the customers' needs and increased the responsiveness of the SCN to increase profitability. In this article, in the presented mathematical model, in addition to the optimal place, capacity, amount of scrap purchased and collected for production in a period, and the amount of conveyed products between factories that existed in the customary supply chain, the selection of factories for AS was made according to the relationship between the risks and benefits of AS in the SCN and the parts of AS for each of the factories were carried out. In the SCN as well as the strategy of AS and RP, a responsive model for the design of the SCN was presented, and LS, delivery time deviations, and penalties for lost sales for increasing customer satisfaction in the cost objective function were considered responsiveness policies. Also, due to uncertainty parameters in the mathematical model, optimization methods under uncertainty based on Aghezzaf et al. [57] were used to increase the model's efficiency. Finally, to solve the MO problem, a solution centered on the augmented ε-constraint was developed.

The consequences of solving the mathematical model show the model's efficiency in creating a Pareto space and a supporter for senior managers in the supply chain. Using data from the steel industry showed that using RP, AS, and LS simultaneously could improve the total cost by 14% and the responsiveness of the SCN by 17%. On the other hand, the calculation results of the presented algorithm based on the augmented ε-constraint method prove the effectiveness of this algorithm. So, using the finding of this article, senior managers in the field of steel can make more productive decisions on the SCN design, using RP, AS, and Ls and increasing responsiveness in the SCN.

According to the consideration of the model under uncertainty in this study, the use of other methods,

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such as fuzzy [60] or different ways of solving models [61], maybe a path for future research. Authors can combine the aspect of industry 5.0 (for example, human-centric) in the article. On the other hand, since the steel industry is one of the most vital sectors in the field of sustainability, presenting a mathematical model based on sustainability [62], [63] is essential for future studies.

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Conflicts of Interest

The researchers certify that the submission is not under review at any other publication and is original work.

References

[1] Abbasian, M., Sazvar, Z., & Mohammadisiahroudi, M. (2023). A hybrid optimization method to design a sustainable resilient supply chain in a perishable food industry. *Environmental science and pollution research*, *30*(3), 6080–6103. DOI:10.1007/s11356-022-22115-8

[2] Romero, D., & Stahre, J. (2021). Towards the resilient operator 5.0: the future of work in smart resilient manufacturing systems. *Procedia cirp*, *104*, 1089–1094. DOI:10.1016/j.procir.2021.11.183

[3] Richey, R. G., Roath, A. S., Adams, F. G., & Wieland, A. (2022). A responsiveness view of logistics and supply chain management. *Journal of business logistics*, *43*(1), 62–91.

[4] Singh, H., Garg, R., & Sachdeva, A. (2018). Supply chain collaboration: A state-of-the-art literature review. *Uncertain supply chain management*, *6*(2), 149–180.

[5] Dolgui, A., Ivanov, D., & Rozhkov, M. (2020). Does the ripple effect influence the bullwhip effect? An integrated analysis of structural and operational dynamics in the supply chain. *International journal of production research*, *58*(5), 1285–1301.

[6] Sabouhi, F., Pishvaee, M. S., & Jabalameli, M. S. (2018). Resilient supply chain design under operational and disruption risks considering quantity discount: A case study of pharmaceutical supply chain. *Computers & industrial engineering*, *126*, 657–672.

[7] Tomlin, B. (2006). On the value of mitigation and contingency strategies for managing supply chain disruption risks. *Management science*, *52*(5), 639–657.

[8] Duong, L. N. K., & Chong, J. (2020). Supply chain collaboration in the presence of disruptions: a literature review. *International journal of production research*, *58*(11), 3488–3507.

[9] Kim, D., & Lee, R. P. (2010). Systems collaboration and strategic collaboration: their impacts on supply chain responsiveness and market performance. *Decision sciences*, *41*(4), 955–981. DOI:10.1111/j.1540-5915.2010.00289.x

[10] Difrancesco, R. M., Meena, P., & Tibrewala, R. (2021). Buyback and risk-sharing contracts to mitigate the supply and demand disruption risks. *European journal of industrial engineering*, *15*(4), 550–581. DOI:10.1504/EJIE.2021.116140

[11] Oh, S. C., Min, H., & Ahn, Y. H. (2021). Inventory risk pooling strategy for the food distribution network in Korea. *European journal of industrial engineering*, *15*(4), 439–462. DOI:10.1504/EJIE.2021.116131

[12] Mafini, C., & Muposhi, A. (2017). Predictive analytics for supply chain collaboration, risk management and financial performance in small to medium enterprises. *Southern african business review*, *21*(1), 311–338.

[13] Shahbaz, M. S., Sohu, S., Khaskhelly, F. Z., Bano, A., & Soomro, M. A. (2019). A novel classification of supply chain risks: a review. *Engineering, technology & applied science research*, *9*(3), 4301–4305.

[14] Pishvaee, M. S., Farahani, R. Z., & Dullaert, W. (2010). A memetic algorithm for bi-objective integrated forward/reverse logistics network design. *Computers and operations research*, *37*(6), 1100–1112. DOI:10.1016/j.cor.2009.09.018

[15] Ramezani, M., Bashiri, M., & Tavakkoli-Moghaddam, R. (2013). A new multi-objective stochastic model for a forward/reverse logistic network design with responsiveness and quality level. *Applied mathematical modelling*, *37*(1–2), 328–344. DOI:10.1016/j.apm.2012.02.032

[16] Martí, J. M. C., Tancrez, J. S., & Seifert, R. W. (2015). Carbon footprint and responsiveness trade-offs in supply chain network design. *International journal of production economics*, *166*, 129–142. DOI:10.1016/j.ijpe.2015.04.016

[17] Hamidieh, A., Naderi, B., Mohammadi, M., & Fazli-Khalaf, M. (2017). A robust possibilistic programming model for a responsive closed loop supply chain network design. *Cogent mathematics*, *4*(1), 1329886. https://doi.org/10.1080/23311835.2017.1329886

[18] Sabouhi, F., Jabalameli, M. S., Jabbarzadeh, A., & Fahimnia, B. (2020). A multi-cut L-shaped method for resilient and responsive supply chain network design. *International journal of production research*, *58*(24), 7353–7381.

[19] Aboolian, R., Berman, O., & Wang, J. (2021). Responsive make-to-order supply chain network design. *Naval research logistics (nrl)*, *68*(2), 241–258.

[20] Azaron, A., Venkatadri, U., & Farhang Doost, A. (2021). Designing profitable and responsive supply chains under uncertainty. *International journal of production research*, *59*(1), 213–225.

[21] Nayeri, S., Ali Torabi, S., Tavakoli, M., & Sazvar, Z. (2021). A multi-objective fuzzy robust stochastic model for designing a sustainable-resilient-responsive supply chain network. *Journal of cleaner production*, *311*, 127691. DOI:10.1016/j.jclepro.2021.127691

[22] Vali-Siar, M. M., & Roghanian, E. (2022). Sustainable, resilient and responsive mixed supply chain network design under hybrid uncertainty with considering COVID-19 pandemic disruption. *Sustainable production and consumption*, *30*, 278–300. DOI:10.1016/j.spc.2021.12.003

[23] Hamidieh, A., & Johari, A. (2022). Blood Supply Chain Network Design Considering Responsiveness and Reliability in Conditions of Uncertainty Using the Lagrangian Relaxation Algorithm. *International journal of research in industrial engineering*, *11*(2), 188–204. http://creativecommons.org/licenses/by/4.0

[24] Ghasemi, P., Hemmaty, H., Pourghader Chobar, A., Heidari, M. R., & Keramati, M. (n.d.). A multi-objective and multi-level model for location-routing problem in the supply chain based on the customer's time window. *Journal of applied research on industrial engineering*. http://www.journal-aprie.com/article_149806.html

[25] Groothedde, B., Ruijgrok, C., & Tavasszy, L. (2005). Towards collaborative, intermodal hub networks. A case study in the fast moving consumer goods market. *Transportation research part e: logistics and transportation review*, *41*(6 SPEC. ISS.), 567–583. DOI:10.1016/j.tre.2005.06.005

[26] Ballot, E., & Fontane, F. (2010). Reducing transportation CO2 emissions through pooling of supply networks: Perspectives from a case study in French retail chains. *Production planning and control*, *21*(6), 640–650. DOI:10.1080/09537287.2010.489276

[27] Pan, S., Ballot, E., Fontane, F., & Hakimi, D. (2014). Environmental and economic issues arising from the pooling of SMEs' supply chains: Case study of the food industry in western France. *Flexible services and manufacturing journal*, *26*(1–2), 92–118. DOI:10.1007/s10696-012-9162-3

[28] Sugiono, A., Rahayu, A., & Wibowo, L. A. (2022). Environmental uncertainty factor, incoterm and implication for a strategic alliance in freight forwarder companies case study in Indonesia. *Asian journal of logistics management*, *1*(1), 1–15. DOI:10.14710/ajlm.2022.14230

[29] Pan, S., Ballot, E., & Fontane, F. (2013). The reduction of greenhouse gas emissions from freight transport by pooling supply chains. *International journal of production economics*, *143*(1), 86–94.

[30] Ouhader, H., & El kyal, M. (2017). Combining facility location and routing decisions in sustainable urban freight distribution under horizontal collaboration: how can shippers be benefited? *Mathematical problems in engineering*, *2017*. DOI:10.1155/2017/8687515

[31] Aloui, A., Hamani, N., Derrouiche, R., & Delahoche, L. (2022). Assessing the benefits of horizontal collaboration using an integrated planning model for two-echelon energy efficiency-oriented logistics networks design. *International journal of systems science: operations \& logistics*, *9*(3), 302–323.

[32] Habibi, M. K. K., Allaoui, H., & Goncalves, G. (2018). Collaborative hub location problem under cost uncertainty. *Computers and industrial engineering*, *124*, 393–410. DOI:10.1016/j.cie.2018.07.028

[33] Arslan, O., Archetti, C., Jabali, O., Laporte, G., & Grazia Speranza, M. (2020). Minimum cost network design in strategic alliances. *Omega (United Kingdom)*, *96*, 102079. DOI:10.1016/j.omega.2019.06.005

[34] Foroozesh, N., Karimi, B., & Mousavi, S. M. (2022). Green-resilient supply chain network design for perishable products considering route risk and horizontal collaboration under robust interval-valued type-2 fuzzy uncertainty: A case study in food industry. *Journal of environmental management*, *307*, 114470. DOI:10.1016/j.jenvman.2022.114470

[35] Dorgham, K., Nouaouri, I., Nicolas, J. C., & Goncalves, G. (2022). Collaborative hospital supply chain network design problem under uncertainty. *Operational research*, *22*(5), 4607–4640. DOI:10.1007/s12351-022-00724-y

[36] Mrabti, N., Hamani, N., & Delahoche, L. (2022). A sustainable collaborative approach to the distribution network design problem with CO2 emissions allocation. *International journal of shipping and transport logistics*, *14*(1–2), 114–140. DOI:10.1504/IJSTL.2022.120676

[37] Ghahremani Nahr, J., & Zahedi, M. (2021). Modeling of the supply chain of cooperative game between two tiers of retailer and manufacturer under conditions of uncertainty. *International journal of research in industrial engineering*, *10*(2), 95–116.

[38] Tang, X., Lehuédé, F., & Péton, O. (2016). Location of distribution centers in a multi-period collaborative distribution network. *Electronic notes in discrete mathematics*, *52*, 293–300. DOI:10.1016/j.endm.2016.03.039

[39] Hendry, L. C., Stevenson, M., MacBryde, J., Ball, P., Sayed, M., & Liu, L. (2019). Local food supply chain resilience to constitutional change: the Brexit effect. *International journal of operations and production management*, *39*(3), 429–453. DOI:10.1108/IJOPM-03-2018-0184

[40] Xames, D., Tasnim, F., Mim, T., & Kiron, A. (2022). COVID-19 and food supply chain disruptions in Bangladesh : impacts and strategies. *International journal of research in industrial engineering*, *11*(2), 155–164.

[41] Mansory, A., Nasiri, A., & Mohammadi, N. (2021). Proposing an integrated model for evaluation of green and resilient suppliers by path analysis, SWARA and TOPSIS. *Journal of applied research on industrial engineering*, *8*(2), 129–149.

[42] Aliahmadi, A., Nozari, H., Ghahremani-Nahr, J., & Szmelter-Jarosz, A. (2022). Evaluation of key impression of resilient supply chain based on artificial intelligence of things (AIoT). *Journal of fuzzy extension and applications*, *3*(3), 201–211.

[43] Aryanezhad, M. B., Jalali, S. G., & Jabbarzadeh, A. (2010). An integrated supply chain design model with random disruptions consideration. *African journal of business management*, *4*(12), 2393-2401.

[44] Jabbarzadeh, A., Fahimnia, B., & Seuring, S. (2014). Dynamic supply chain network design for the supply of blood in disasters: A robust model with real world application. *Transportation research part e: logistics and transportation review*, *70*, 225–244.

[45] Rezapour, S., Farahani, R. Z., & Pourakbar, M. (2017). Resilient supply chain network design under competition: A case study. *European journal of operational research*, *259*(3), 1017–1035. DOI:10.1016/j.ejor.2016.11.041

[46] Margolis, J. T., Sullivan, K. M., Mason, S. J., & Magagnotti, M. (2018). A multi-objective optimization model for designing resilient supply chain networks. *International journal of production economics*, *204*, 174–185.

[47] Hasani, A., Mokhtari, H., & Fattahi, M. (2021). A multi-objective optimization approach for green and resilient supply chain network design: a real-life case study. *Journal of cleaner production*, *278*, 123199. https://doi.org/10.1016/j.jclepro.2020.123199

[48] Hosseini-Motlagh, S.-M., Samani, M. R. G., & Shahbazbegian, V. (2020). Innovative strategy to design a mixed resilient-sustainable electricity supply chain network under uncertainty. *Applied energy*, *280*, 115921. https://doi.org/10.1016/j.apenergy.2020.115921

[49] Zahiri, B., Zhuang, J., & Mohammadi, M. (2017). Toward an integrated sustainable-resilient supply chain: A pharmaceutical case study. *Transportation research part e: logistics and transportation review*, *103*, 109–142.

[50] Mohammed, A., Harris, I., Soroka, A., & Nujoom, R. (2019). A hybrid MCDM-fuzzy multi-objective programming approach for a G-resilient supply chain network design. *Computers & industrial engineering*, *127*, 297–312.

[51] Sazvar, Z., Tafakkori, K., Oladzad, N., & Nayeri, S. (2021). A capacity planning approach for sustainable-resilient supply chain network design under uncertainty: A case study of vaccine supply chain. *Computers & industrial engineering*, *159*, 107406. https://doi.org/10.1016/j.cie.2021.107406

[52] Lotfi, R., Mehrjerdi, Y. Z., Pishvaee, M. S., Sadeghieh, A., & Weber, G. W. (2021). A robust optimization model for sustainable and resilient closed-loop supply chain network design considering conditional value at risk. *Numerical algebra, control and optimization*, *11*(2), 221–253. DOI:10.3934/naco.2020023

[53] Philsoophian, M., Akhavan, P., & Abbasi, M. (2021). Strategic alliance for resilience in supply chain: A bibliometric analysis. *Sustainability (Switzerland)*, *13*(22), 12715. DOI:10.3390/su132212715

[54] Tordecilla, R. D., Juan, A. A., Montoya-Torres, J. R., Quintero-Araujo, C. L., & Panadero, J. (2021). Simulation-optimization methods for designing and assessing resilient supply chain networks under uncertainty scenarios: A review. *Simulation modelling practice and theory*, *106*, 102166. DOI:10.1016/j.simpat.2020.102166

[55] Ivanov, D., & Dolgui, A. (2019). Low-Certainty-Need (LCN) supply chains: a new perspective in managing disruption risks and resilience. *International journal of production research*, *57*(15–16), 5119–5136. DOI:10.1080/00207543.2018.1521025

[56] Hosseini, S., Ivanov, D., & Dolgui, A. (2019). Review of quantitative methods for supply chain resilience analysis. *Transportation research part E: logistics and transportation review*, *125*, 285–307. DOI:10.1016/j.tre.2019.03.001

[57] Aghezzaf, E. H., Sitompul, C., & Najid, N. M. (2010). Models for robust tactical planning in multi-stage production systems with uncertain demands. *Computers and operations research*, *37*(5), 880–889. DOI:10.1016/j.cor.2009.03.012

[58] Mavrotas, G. (2009). Effective implementation of the ε-constraint method in multi-objective mathematical programming problems. *Applied mathematics and computation*, *213*(2), 455–465.

[59] Pishvaee, M. S., Razmi, J., & Torabi, S. A. (2014). An accelerated Benders decomposition algorithm for sustainable supply chain network design under uncertainty: A case study of medical needle and syringe supply chain. *Transportation research part e: logistics and transportation review*, *67*, 14–38.

[60] Farnam, M., & Darehmiraki, M. (2022). Supply chain management problem modelling in hesitant fuzzy environment. *Journal of fuzzy extension and applications*, *3*(4), 317–336.

[61] Najafi, S. E., Salahshour, S., & Rahmani Parchikolaei, B. (2022). Optimizing supplier selection for a construction project by a cash-flow approach using a hybrid metaheuristic algorithm. *Big data and computing visions*, *2*(2), 69–79.

[62] Ghahremani-Nahr, J., Nozari, H., & Najafi, S. E. (2020). Design a green closed loop supply chain network by considering discount under uncertainty. *Journal of applied research on industrial engineering*, *7*(3), 238–266.

[63] Saffari, H., Makui, A., Mahmoodian, V., & Pishvaee, M. S. (2015). Multi-objective robust optimization model for social responsible closed-loop supply chain solved by non-dominated sorting genetic algorithm. *Journal of industrial and systems engineering*, *8*(3), 42–58.

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Paper Type: Review Paper

Measurement of Service Quality and Customer Satisfaction in the SME Industry: Literature Study

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Abstract

SMEs is one of the pillars that can improve people's lives and is very meaningful for the government. In order for SMEs to continue to develop, even increase, it is necessary to measure service quality and customer satisfaction so that SMEs can identify weaknesses in their business as evaluation material. The research method begins by reviewing the literature related to the SMEs service industry, classifying, choosing what is appropriate for this research. The results of the research show that several methods can be used to measure, analyze, evaluate, and develop products. The KANO method with functional dysfunction assessment to identify customer desires based on attributes can have a significant influence on customer satisfaction. Servqual with a 5 gap analysis model for customer satisfaction analysis, IPA can be used to measure, test, analyze and determine service priority improvements, while QFD is broader. In addition to evaluating the quality of services and products, it is also for development or innovation and is not limited to the service industry but can be used to develop products for the manufacturing industry. Every business needs to be evaluated to improve performance, several approaches such as KANO, Servqual, IPA, QFD can be used as a reference for measuring, evaluating and developing to continue to improve and develop the business.

Keywords: SMEs, KANO, Servqual, IPA, QFD, Quality service.

1 | Introduction

Covid-19 pandemics have occurred almost all over the world, one of those affected by the outbreak is the economic sector that affects the lives of the people. Many people lost their jobs, businesses went bankrupt and it was necessary to find alternative businesses to survive in uncertain conditions. To restore the economy, the government needs to involve the community so that the economic situation returns to stability. For the community, Small and Medium Enterprises (SMEs) are an alternative to improve living standards in the family environment. The need for the role of society to develop SMEs need to measure performance, evaluate services and customer satisfaction related to products. Several approaches can be used to measure, evaluate, and develop products. Several approaches have been used in previous research in various areas of the SMEs industry to identify consumer needs, analyze and determine improvements based on priorities for service quality, and Quality Function Deployment (QFD) can be used for product development.

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Almost all countries in the world are experiencing a Covid-19 pandemic. One of the countries that is not immune to the COVID-19 pandemic is Indonesia. Countries located in Southeast Asia are also experiencing the COVID-19 outbreak. The impact of the COVID-19 pandemic has occurred in all sectors, one of the most influential sectors is the economy, which affects people's lives in Indonesia. Due to the Covid-19 pandemic, manufacturing industry sector experienced a decline in production and stock prices experienced a sharp decline, so many lost their jobs [1]. One of the industrial areas dominated by the manufacturing industry experienced layoffs due to various factors, such that, workers affected by layoffs had to continue to earn income to survive. One alternative to still have an income is to open a business and one form of business that is carried out is SMEs. SMEs are one of the pillars of the community's economy and a pillar of economic revival in Indonesia.

In running a SMEs business, of course, there are many obstacles, both internal and external. External constraints can come from consumers, including satisfaction with products and services. This will affect the business. Constraints are problems that must be resolved in order to find a solution. In running a business, when a problem arises, it needs to be resolved for the continuity of the business being run. For this reason, it is necessary to evaluate to find out the weaknesses of the business being conducted. The evaluation is conducted as a result of the community's evaluation of the products produced, one of the evaluations using the method of QFD for product satisfaction and customer service. The quality function application method is widely used in research. In addition to evaluating product and service satisfaction, the method can also be used for product development. Product quality cannot be known without evaluation. To be able to evaluate a product, the consumer knows how the product is. To determine product quality, customer needs are identified by determining quality characteristics that are then converted to product design using the QFD method [2]. In the study, the QFD approach uses a 3 -phase methodological framework by identifying user needs, customer voice, VOC data processing; develop a fuzzy method based on reference comparisons to determine the relative importance of consumer needs in anticipation of uncertainties related to respondents' qualitative assessments and performance importance analysis to determine improvement priorities for customer satisfaction.

2 | Research Method

This research is conducted by seeking information sources through various national and international journals related to the study of literature, theory and concepts, which can be used as a the framework of thinking in this research is focused on the service industry. In this literature review, a systematic literature review approach was used to find references appropriate to the field of study [3]. As a first step in research, a framework for thinking in a literature review is needed as shown in the following *Fig. 1*.

The framework of thinking in this research is focused on the service industry, so that the theories, concepts and results of previous research related to the service industry in various fields are still relevant to the research objectives. The initial step of the research is to find ideas based on the conditions of the COVID-19 pandemic that occurred in Indonesia. Collect and review references related to servqual. The results of this literature review become one of the guidelines in research that is used to analyze service quality and customer satisfaction on the performance of the SME service industry. Collecting references after finding research ideas. The research idea is based on the conditions of the covid-19 pandemic that occurred in Indonesia.

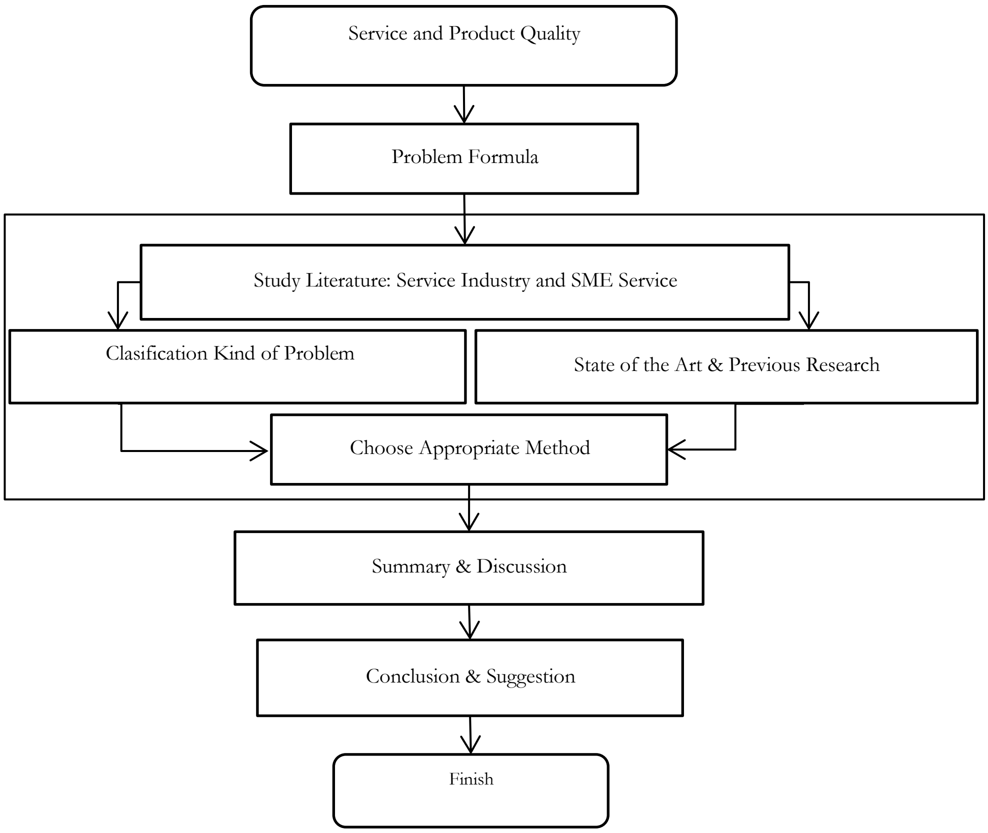

Fig. 1. Study framework.

The literature review is taken from journals published in the last 10 years and 1 reference for 10 years. Journals are taken from Google Scholar and Scopus as well as journal managers where the results of this research will be published. Previous research is a reference that forms the basis of further research, some previous research in the service sector that is a reference is listed in the following table:

Table 1. Previous research.

No	Researcher	Method	Result
1	Anggraini et al. [4]	SWOT, QFD, 4P marketing Mix	QFD, marketing mix and SWOT can analyze product attributes that are priorities for evaluation.
2	Fadillah [5]	Servqual, Interest Performance Analysis (IPA), Customer Satisfaction Index (CSI)	Servqual, IPA, CSI are methods for testing and analyzing services and prioritize for improvement.
3	Farhatan and Harisudin [6]	QFD	Prioritization improvement on technical requirements with the QFD approach.
4	Alfatiyah [7]	Servqual, QFD	The results of identification, evaluation and analysis using Servqual and QFD approaches show that service quality with the lowest percentage level is a priority for improvement.
5	Lukman and Wulandari [8]	QFD	Prioritize the improvement of quality attributes and customer satisfaction based on the results of analysis using KANO and QFD methods.
6	Rotar and Kozar [9]	KANO	Measuring consumer satisfaction and desire can use the KANO method.

Table 1. Continued.

No	Researcher	Method	Result
7	Septariadi et al. [10]	KANO, servqual, QFD	For culinary products, the QFD method can help identify critical product attributes that are improvement priorities.
8	Marisa and Darmawan [11]	QFD, Servqual, IPA	Technical requirements with the QFD method are a priority for improvement proposals in improving service quality.
9	Kurnia and Listanti [12]	QFD	Product development according to user demand is a priority based on technical requirements with QFD method.
10	Wibawa et al. [13]	Servqual, KANO, QFD	Improvements are prioritized in the field by identifying attributes to improve the quality of service to customers.
11	Rahmawan [14]	QFD	In the field of education, competencies have a strong relationship with the abilities of students according to the needs of the company.
12	Yolanda et al. [15]	CSI, IPA	To increase the level of consumer satisfaction, product taste, sales promotion, payment, display, labels become a priority.
13	Ginting and Yazid Ali [16]	KANO, QFD, Triz	The implementation of KANO, QFD and TRIZ methods is the right tool for improvement to improve the quality in the field of educational services.
14	Song et al. [17]	QFD	QFD is an approach to analyzing the quality of customer service.
15	Ishak et al. [18]	QFD, value engineering	To improve product quality and development, it can be done with QFD approach and value engineering to evaluate appearance related.
16	Purba et al. [19]	QFD	The composition of chocolate content is a top priority in product development based on evaluation by QFD method.
17	Pourkhandania et al. [20]	QFD, servqual	Technical requirements become an improvement priority based on analysis with a combination of Servqual, QFD and Fuzzy.
18	Syamsul Anwar et al. [21]	QFD	In culinary products, taste, variation and technical response are the priority of improvement based on the QFD method.
19	Cetinkaya et al. [22]	QFD	QFD is used in education to analyze course requirements in industrial engineering study programs to enhance learning.
20	Popoffa and Millet [23]	QFD, CSP	The implementation of QFD can be used to know the needs of consumers, products accepted by the community to improve sales performance.
21	Rif'ah et al. [24]	QFD, KANO	The Kano method concludes that the preferred consumer attributes are product quality visually, taste, texture, and aroma.
22	Prasad and Chakraborty [25]	QFD	QFD-based applications can be integrated to know the customer's voice in material selection.
23	Gangurde and Patil [26]	QFD, Canoeing	The priority of repairs based on technical needs and user voice is the result of identification with the level of importance through QFD.

Table 1. Continued.

No	Researcher	Method	Result
24	Sukmaningsih and Sri [27]	VE, QFD	The integration of VE and QFD can translate the emotional and functional needs of consumers into product development and consumer desires.
25	Xie et al. [28]	QFD, ANP, Fuzzy	Factors influencing customer satisfaction assessment are technical characteristics and consumer voice.
26	Nindiani et al. [29]	IPA	To determine the status of indicators related to product and service quality using the IPA method and generate improvement priorities to product quality, and service quality that are in quadrant A.
27	Hallencreutz and Parmler [30]		One of the indicators that influences a company's image is customer satisfaction.
28	Mensah and Mensah [31]	Servqual	Service quality has a significant effect on customer satisfaction, but customer satisfaction does not affect service quality for not repurchasing.
29	Chen et al. [32]	IPA KANOE	Effectiveness of KANO implementation methodology, IPA recommends optimal service strategies.
30	Ali et al. [33]	Customer satisfaction	The impact of technical and functional service quality on customer satisfaction and loyalty is influenced by privacy issues in online meetings.
31	Kowalik and Klimecka Tatar [34]	Servqual	The results of the analyzed processes form the basis for continuous improvement, so that service quality can be implemented into process management.
32	Medberg and Gronroos [35]		Service quality is a way to serve customers to focus on quality management.
33	Majid et al. [36]	Servquality	To increase customer loyalty, reputation and continuous improvement, improvement is needed from all aspects, including product quality, services, and corporate image.
34	Rachman et al. [37]	QFD	The basis for formulating real customer needs and customer complaints can be met with suggestions from the identification of technical features and critical parts.
35	Ramya et al. [38]	Servqual	To meet customer expectations more efficiently and effectively, consistency in serving customers is required by maintaining the quality of services and products.
36	Saragih et al. [39]	SWOT QFD	For product development according to customer expectations, a strategy to determine attributes based on a priority scale is required.
37	Fajri Hasibuan [40]	Fuzzy servqual	Consumer evaluation wants to prioritize improvements on the quality dimension of empathy criteria.
38	Permata and Dwiyanto [41]	QFD, IPA	Quality improvement on technical attributes is a priority, while customer requirements attributes are based on performance analysis of importance.
39	Mohammad Salameh et al. [42]	Servqual	Customer satisfaction is greatly influenced by the quality of service, but the effect can vary according to the level of technological advancement.
40	Tuncer et al. [43]	Servqual	Customer satisfaction is influenced by the quality of service so that it becomes a positive value in customer evaluation.
41	Scheidt and Chung [44]	Servqual	To improve customer service, it is necessary to measure and analyze KPIs so that they are more effective.

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Table 1. Continued.

No	Researcher	Method	Result
42	Dam and Dam [45]	Servqual	Customer satisfaction and customer loyalty to service are interrelated.
43	Lukman and Wulandari [8]	Canoeing QFD	Product development prioritizes technical response and consumer demand.
44	Ingaldi and Ulewicz [46]	Servqual IPA	Servqual's approach to analysis and evaluation of service quality in general and improvement priorities are based on the results of the introduction with IPA.
45	Situmorang et al. [47]	QFD	Factors related to service quality become a priority for improvement.
46	Rottie et al. [48]	Dinerserv ZOT QFD	Technical service and response is a priority for improvement.
47	Ainu Syukri [49]	CSI	The highest gap between consumer expectations and service perceptions is a priority for improvement.
49	Berkes [50]	FIRE	Significant dimensions in the form of comfort in the culinary area become a priority for improvement.
50	Tursch et al. [51]	TRIZ QFD	The TRIZ method can shorten the process while QFD is capable of translating the user's wishes.
51	Jamilatur et al. [52]	QFD	Technical requirements in the production process are a priority for improvement.
52	Gozaly and Talar [53]	Servqual IPA	Consumer demand affects the quality of service.
53	Ginting et al. [54]	QFD	The results of the literature review indicate that the QFD method shows effectiveness in quality and product management.
54	Dyana et al. [55]	QFD	The results show product quality (taste) is a priority for improvement.
55	Nurwulan et al. [56]	Servqual	Research using the servqual method shows that customer perceptions of service are not in line with expectations.
56	Novrianto [57]	IPA	The results of the analysis with IPA show that the quality of service on the physical dimension is still unsatisfactory.

3 | Literature Research

KANO

Use of KANO method can identify the attributes that have the most influence on customer satisfaction, while QFD can identify priorities in improving product quality [8]. To know the properties desired by customers and the magnitude of their influence, it is necessary to analyze them first. One of the suitable methods used is a combination of KANO and QFD methods, an attribute that is an improvement priority is an important attribute for the user. For culinary products, the KANO method concludes that the preferred consumer attributes are product quality visually, taste, texture, and aroma [24]. Combination of KANO, QFD and TRIZ methods is a suitable improvement tool to improve the quality of educational services [16], while the KANO method is generally used to measure user satisfaction and desire [9].

Table 2. KANO assessment.

Customer Requirements		Disfunctional				
		1 Like	2 Must be	3 Neutral	4 Live with	5 Dislike
Functional	1. Like	Q	A	A	A	O
	2. Must be	R	I	I	I	M
	3. Neutral	R	I	I	I	M
	4. Live with	R	I	I	I	M
	5. Dislike	R	R	R	R	Q

Step 1. Answers between functional and non-functional were combined for each attribute of the number of respondents.

Step 2. Convert the answers into the forms A, M, O, R, Q, and I, then calculate the components in each question.

Step 3. Using the Blauth formula, define the KANO category for each attribute.

Step 4. After calculating by category, the customer satisfaction coefficient is sought by the equation.

$$\text{Better Satisfaction)} = \frac{A+O}{A+O+M+I}.$$

$$\text{Worse ketidakpuasan)} = -\frac{O+M}{A+O+M+I}.$$

Servqual

Service quality has a significant effect on customer satisfaction, but customer satisfaction does not affect service quality for non–repurchase [31]. Service quality to customer satisfaction and loyalty is influenced by privacy in online meetings [58]. The outcome of a process becomes the basis for continuous improvement, so that service quality can be implemented into process management [34]. To increase customer loyalty, reputation, and continuous improvement, it is necessary to improve all aspects, including product quality, services, and corporate image using the servqual method [36]. Servqual can also be used to meet customer expectations more efficiently and effectively, it requires consistency in serving customers by maintaining the quality of services and products [59]. Evaluation of customer satisfaction with fuzzy and servqual methods is used to determine the priority of improvement on the quality dimensions of the combined servqual and fuzzy empathy criteria [43], [40]. The level of technological advancement also significantly affects customer satisfaction [42]. To improve customer service, it is necessary to measure and analyze KPIs so that they are more effective [44]. Customer satisfaction and customer loyalty to service are interrelated [45].

Servqual is a service quality model as a reference in service management and marketing, developed by Parasuraman with the term gap analysis model related to customer satisfaction and known as the five main gaps of servqual [56]:

I. Gap 1 is the gap between customer expectations and management perceptions (knowledge gap).
II. Gap 2 is the gap between management's perceptions of consumer expectations and service quality specifications (standards gap).
III. Gap 3 is the gap between service quality specification and service delivery (delivery gap).
IV. Gap 4 is the gap between service delivery and external communication (communication gap).
V. Gap 5 is the gap between perceived services and expected services (service gap).

The research variables were arranged with servqual based on five dimensions of quality and the number of respondents was determined based on the following equation [53].

$$n = \pi(1-\pi)\left(\frac{Z}{E}\right)^2,$$

n = Minimum number of samples.

Z = Standard nominal value according to confidence level (with a 95% confidence level, Z = 1.96).

π = Population share (0.5).

E = Maximum allowable error (10%).

Importance Performance Analysis

The significance performance analysis method was first developed by Martilla and James [60] with the aim of measuring the level of consumer satisfaction with a product or service in various fields [41]. One area that is now widely used by the public in online meetings, service quality, and customer satisfaction is influenced by privacy concerns during online meetings [58]. In its development, the IPA method is combined with servqual and CSI to test and analyze, as well as determine service priority improvements, based on customer satisfaction levels [5], [15]. The gap between consumer expectations and perceptions of service and product quality is a priority for improvement based on an analysis using IPA method shown in quadrant A Cartesian diagram [29], [49]. Meanwhile, significant dimensions in the form of comfort became a priority for improvement [61], the results of the analysis with IPA show that the quality of service on the physical dimension is still unsatisfactory [57]. Service quality is a way to serve customers to focus on quality management [35] and consumer demand affects the quality of service [53]. Servqual's approach to analysis and evaluation of service quality in general and improvement priorities are based on the results of the introduction with IPA [46]. Effectiveness of KANO implementation methodology, IPA recommends optimal service strategies [32]. The data needed for IPA analysis, by spreading questionnaires on level of importance and average level of expectation value of service and product quality are described in following formula:

$$\overline{X}_1 = \frac{\sum_{i=1}^{k} Xi}{n}.$$

$\overline{X}$ = Average score of satisfaction level.

$\overline{X}_i$ = Respondent satisfaction level score to-i.

n = Number of respondents.

$$\overline{X}_1 = \frac{\sum_{i=1}^{k} Xi}{n}.$$

$\overline{\overline{Y}}$ = Average score of importance.

$\overline{Y}_i$ = The score of the respondent's importance level to-i.

n = Number of respondents.

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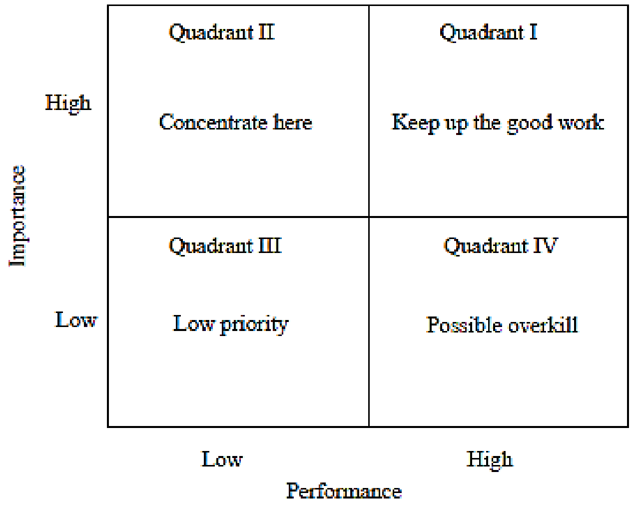

Fig. 3. Traditional IPA matrix [32].

The attribute elements in the IPA diagram consist of 4 quadrants. Quadrant I (top priority), this quadrant contains attributes that are considered important by customers, but these attributes have not met customer expectations or the level of customer satisfaction is still far from expectations. Attributes that are in this quadrant are a priority for immediate improvement. Quadrant II (maintain achievement), this quadrant contains attributes that are considered important by customers but are in line with expectations or customer satisfaction is already better than the attributes in quadrant I. This quadrant is in a category that must be maintained and maintained. Quadrant III (low priority), this quadrant contains attributes that are considered less important by customers and in fact the performance is not too special. Quadrant IV (excessive), this quadrant contains attributes that are considered less important by customers and even excessive, so that the attributes in this quadrant can be reduced to save costs [57].

Quality Function Deployment

The use of QFD is one of the methods used to evaluate the quality of services & products or to develop products. Currently, many service or manufacturing industries use the QFD method to develop products or to determine customer satisfaction with the products they produce. QFD method is very flexible because it is not limited to specific industries, so it can help organizations and industries in solving problems. In culinary products, taste, variation, and technical response are priority improvements based on the QFD method [21].

The basis for formulating real customer needs and customer complaints can be met with recommendations from the identification of technical features and critical parts in the sale of clothing [37]. In addition, a combination of QFD and other methods can be an alternative in product design selection to produce the best concept solution by selecting a combination score, including QFD, competitiveness (quality function–AHP), development design efficiency (data envelopment analysis-DEA) [62]. QFD is a method for organizations or companies in developing and improving product quality according to consumer expectations [63].

House of Quality

The target value and the benchmark approach with the QFD approach are determinants in determining the level of importance of each variable. To improve service quality using House of Quality (HoQ) method, obtain percentage value and weighted value with improvement priority starting from the lowest percentage level variable [6], [7] and priority for SME cuisine evaluation with SWOT, QFD and marketing mix [4]. Priority for improvement based on technical needs and user voice is the result of identification with the level of importance through QFD and KANO [25], [64]. QFD helps identify critical product attributes, service quality, development, and areas of improvement to improve customer service quality, which is a priority improvement [10]–[13]. Technical requirements are a priority for improvement based on analysis with a combination of servqual, QFD and Fuzzy [52], [65], and quality and products [18]. QFD is an approach to analyze the quality of services & consumer desires [17], [51]. QFD method can identify the quality of taste in beverages, which is key in product development based on QFD method evaluation [19] for product development according to customer expectations, strategy for attribute determination based on priority scale [39] is required. QFD implementation can be used to know consumer needs, products accepted by society to improve sales performance [66]. QFD education is used for analyzing course requirements in industrial engineering study programs to enhance learning [66]. QFD-based applications can be integrated to find out customer voice in material selection [25]. Factors related to service quality are priorities for improvement [3]. The integration of VE and QFD can translate the emotional and functional needs of consumers in product development and consumer desires [27].

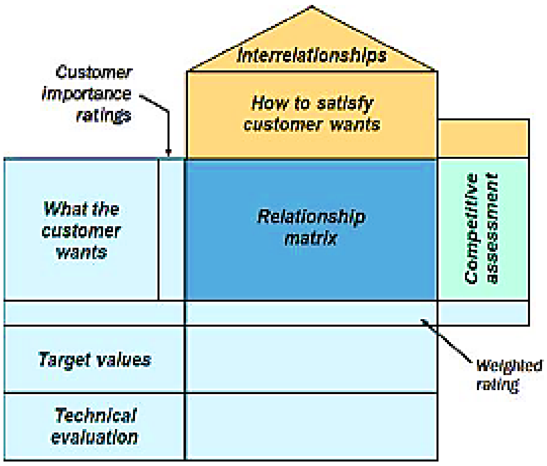

Fig. 4. Quality house [67].

4 | Result and Discussion

Several methods can be used to determine service quality in the service industry. In a literature review, the KANO method developed by Noriako [68] can identify customer desires by taking several steps to evaluate answers between functional and non-functional and using the Blauth formula. Servqual is known as the top 5 gaps or gap analysis model related to customer satisfaction. Gap 5 is a gap that is often used in the analysis of customer satisfaction because one of these gaps is related to the perception of service. Importance Performance Analysis (IPA) is used to measure customer satisfaction, test, analyze, determine several attributes that are priority for improvement based on the highest gap between consumer expectations and perceptions depicted in the Cartesian diagram in quadrant A. Furthermore, QFD analysis is carried out to determine the highest level of importance which is a priority for product/service improvement or development. QFD is not limited to any particular industry, making it more flexible to solve service, product and development related issues. QFD is described in the form of a HoQ which consists of customer requirements, planning matrix, technical requirements, communication matrix, and technical evaluation.

5 | Conclusions and Recommendations

To determine performance of the service industry, several methods can be used. One of KANO's approaches to functional dysfunctional assessment is by identifying customer desires based on attributes that have a significant influence on customer satisfaction. Servqual, with a 5 gap analysis model for customer satisfaction analysis, IPA can be used to measure, test, analyze and determine service priority improvements based on the highest gaps that are in quadrant A of the Cartesian diagram, while QFD can be used to determine priority improvements based on the highest value obtained of the relationship between customer need and technical response. In addition to evaluating service and product quality,

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QFD can be used when developing or innovating and is not limited to the service industry but can be used to develop manufacturing industry products. To improve performance, several approaches such as KANO, Servqual, IPA, QFD are references in measuring, evaluating and developing as well as continuous improvement.

References

[1] Malfrita, P., & Sari, A. (2022). The impact of the COVID-19 pandemic on share prices in manufacturing industrial companies listed on the Indonesian Stock Exchange. *Journal of accounting economic research*, *6*(1), 54–62.

[2] Singh, R. K., Rajput, V., & Sahay, A. (2018). A literature review on quality function deployment (QFD). *IAETSD journal for advanced research in applied sciences*, *5*(8), 245–250.

[3] Ten Ham-Baloyi, W., & Jordan, P. (2016). Systematic review as a research method in post-graduate nursing education. *Health sa gesondheid*, *21*(0), 120–128. DOI:10.1016/j.hsag.2015.08.002

[4] Anggraini, R., & Nursanti, E. (2021). Proposed management strategy to increase bread sales at Swan Cake & Malang Bakery. *Journal valtech*, *4*(2), 179–187.

[5] Hadining, A. F. (2020). Analysis of ABC laundry customer satisfaction using the service quality, importance performance analysis (IPA) and customer satisfaction index (CSI) methods. *Journal technic industry*, *15*(1), 1. DOI:10.14710/jati.15.1.1-10

[6] Farhatan, L. H. (2020). Product and service quality in an effort to increase business competitiveness (case study of Semara Coffee in BSD, South Tangerang). *Familiar champion*, *5*(1), 43–54.

[7] Alfatiyah, R. (2018). Analysis of the quality of advertising services using a combination of servqual and quality function deployment (Qfd) methods to increase customer satisfaction. *Scientific journal of industrial engineering and management*, *1*(1), 1–7.

[8] Lukman, M., & Wulandari, W. (2018). Increasing the quality of chocolate products by integrating Kano and QFD methods. *Industrial engineering journal*, *19*(2), 190. DOI:10.22219/jtiumm.vol19.no2.190-204

[9] Rotar, L. J., & Kozar, M. (2017). The use of the kano model to enhance customer satisfaction. *Organizacija*, *50*(4), 339–351. DOI:10.1515/orga-2017-0025

[10] Septariadi, O., Agus, I., Suhendra, A., & Praptono, I. B. (2019). Plan to improve the quality of Thai tea products from Roffee's Melty Pudding using the QFD method. *E-proceeding of engineering*, *6*(2), 7385–7391.

[11] Marisa, A., & Darmawan, M. (2019). Improving the quality of customer service using the QFD method (Case Study at the Unyil Venus Bogor Bakery). *Journal of industrial systems engineering and optimization*, *01*(1), 44–50.

[12] Kurnia, T. E., & Listanti, A. T. (2019). Identify consumer preferences for red guava cracker products using the QFD method. *Asymmetric journal: scientific journal of engineering & innovation*, *1*(2), 113–123. DOI:10.35814/asiimetrik.v1i2.820

[13] Wibawa, J., Meyliana, Widjaja, H. A. E., & Hidayanto, A. N. (2017). Integrating IS success model, SERVQUAL and kano model into QFD to improve hospital information system qualit. *International conference on information management and technology* (pp. 29–34). DOI:10.1109/ICIMTech.2016.7930297

[14] Rahmawan, A. (2017). Implementation of quality function deployment (QFD) in agro-industrial technology curriculum. *Agroindustrial technology journal*, *1*(1), 10–21.

[15] Yolanda, V., Suyono, & Wijayanti, I. K. E. (2020). Consumer satisfaction analysis of salak chips products, Sleman Regency, Yogyakarta. *Forum agribisnis*, *10*(2), 131–144.

[16] Ginting, R., & Ali, A. Y. (2014). Improvement of educational service using KANO, QFD and triz : a case study. *Journal of teaching and education*, *3*(1), 13–27.

[17] Song, C., Wang, J. Q., & Li, J. B. (2020). New framework for quality function deployment using linguistic Z-numbers. *Mathematics*, *8*(2), 224. https://doi.org/10.3390/math8020224

[18] Ishak, A., Ginting, R., Suwandira, B., & Fauzi Malik, A. (2020). *Integration of kano model and quality function deployment (QFD) to improve product quality: a literature review* [presentation]. IOP conference series: materials science and engineering (Vol. 1003, p. 012022). DOI: 10.1088/1757-899X/1003/1/012025

[19] Purba, H. H., Syamsul Maarif, M., Yuliasih, I., & Hermawan, A. (2018). Product development of chocolate with quality function deployment approach: A case study in SMEs chocolate industry in Indonesia. *IOP conference series: earth and environmental science*, *209*(1). DOI:10.1088/1755-1315/209/1/012011

[20] Pourkhandani, M. H., Iranban, S., & Seyedi, S. (2014). QFD application using combined ANP-DEMATEL approach for improving service quality: a Case study of dental clinic. *International journal of applied research in industrial engineering*, *1*(2), 112–129.

[21] Anwar, S., Palba, I. R., Jasril, & Yunizurwan. (2014). *Application of the quality function deployment method to improve the quality of local chocolate products [presentation]*. BKSTI national seminar on industrial engineering (pp. 79–84). http://dx.doi.org/10.13140/RG.2.1.4512.3048

[22] Cetinkaya, C., Kenger, O. N., Diri Kenger, Z., & Ozceylan, E. (2019). Quality function deployment implementation on educational curriculum of industrial engineering in university of gaziantep. *Industrial engineering in the big data era: selected papers from the global joint conference on industrial engineering and its application areas* (pp. 67–78). Springer International Publishing.

[23] Popoff, A., & Millet, D. (2017). Sustainable life cycle design using constraint satisfaction problems and quality function deployment. *Procedia cirp*, *61*, 75–80.

[24] Rif'ah, A., Sitania, F. D., & Gunawan, S. (2020). Designing lai pie product by using kano model and QFD method. *Journal agritechno*, *13*(2), 112–119. DOI:10.20956/at.v13i2.362

[25] Prasad, K., & Chakraborty, S. (2013). A quality function deployment-based model for materials selection. *Materials and design*, *49*, 525–535. DOI:10.1016/j.matdes.2013.01.035

[26] Gangurde, S. R., & Patil, S. S. (2018). Benchmark product features using the KANO-QFD approach: a case study. *Benchmarking: an international journal*, *25*(2), 450–470.

[27] Sukmaningsih, N., & Asih, A. M. S. (2020). Kansei engineering, quality function deployment, dan product development: studi literatur. *Gadjah mada university national seminar on industrial engineering* (pp. 104–110). Gadjah University. http://repository.ugm.ac.id/276406/

[28] Xie, J., Qin, Q., & Jiang, M. (2020). Multiobjective decision-making for technical characteristics selection in a house of quality. *Mathematical problems in engineering*, *2020*, 1–12.

[29] Nindiani, A., Hamsal, M., & Purba, H. H. (2018). Product and service quality analysis: an empirical study of customer satisfaction in a Bakery. *Binus business review*, *9*(2), 95–103. DOI:10.21512/bbr.v9i2.4257

[30] Hallencreutz, J., & Parmler, J. (2021). Important drivers for customer satisfaction--from product focus to image and service quality. *Total quality management & business excellence*, *32*(5–6), 501–510.

[31] Mensah, I., & Mensah, R. D. (2018). Effects of service quality and customer satisfaction on repurchase intention in restaurants on University of Cape Coast campus. *Journal of tourism, heritage & services marketing*, *4*(2), 27–36.

[32] Chen, L. F., Chen, S. C., & Su, C. T. (2018). An innovative service quality evaluation and improvement model. *Service industries journal*, *38*(3–4), 228–249.

[33] Ali, B. J., Akoi, S., Saleh, P. F., & Sardar, Z. (2021). Factors shaping customer satisfaction with residential flats: evidence from Sulaymaniyah city. *Black sea journal of management and marketing*, *2*(2), 1–12.

[34] Kowalik, K., & Klimecka-Tatar, D. (2018). The process approach to service quality management. *Production engineering archives*, *18*(18), 31–34. DOI:10.30657/pea.2018.18.05

[35] Medberg, G., & Grönroos, C. (2020). Value-in-use and service quality: do customers see a difference? *Journal of service theory and practice*, *30*(4–5), 507–529. DOI:10.1108/JSTP-09-2019-0207

[36] Majid, M. A. A., Samsudin, A., Noorkhizan, M. H. I., Zaki, M. I. M., & Bakar, A. M. F. A. (2018). Service quality, food quality, image and customer loyalty: an empirical study at a hotel restaurant. *International journal of academic research in business and social sciences*, *8*(10), 1432–1446. DOI:10.6007/ijarbss/v8-i10/5310

[37] Rachman, A. T., Suhendra, A. A., & Tripiawan, W. (2019). Proposal to improve the quality of offline sales services at the guteninc store using the quality function deployment (QFD) Method. *Eproceedings of engineering*, *6*(1), 1882–1889.

[38] Ramya, N., Kowsalya, A., & Dharanipriya, K. (2019). Service quality and its dimensions. *EPRA international journal of research & development*, *4*(2), 38–41.

[39] Saragih, L. L., Simarmata, E., Aloina, G., Tarigan, U. P. P., Ramadhani, V. B., & Ginting, S. E. F. (2020). Product development of canned fish using SWOT and quality function deployment (QFD). *AIP conference proceedings* (pp. 2227). DOI:10.1063/5.0001050

[40] Fajri Hasibuan, C. (2020). The measurement of customer satisfaction towards the service quality at xyz wholesale by using fuzzy service quality method. *IOP conference series: materials science and engineering*, *909*(1), 0–6. DOI:10.1088/1757-899X/909/1/012053

[41] Permata, V. I., & Dwiyanto, B. M. (2020). Improving restaurant quality with the quality function deployment (QFD) approach. *Diponegoro journal of management*, *9*(4), 1–15.

[42] Salameh, A. A. M., Ahmad, H., Zulhumadi, F., & Abubakar, F. M. (2018). Relationships between system quality, service quality, and customer satisfaction: M-commerce in the Jordanian context. *Journal of systems and information technology*, *20*(1), 73–102. DOI:10.1108/JSIT-03-2017-0016

[43] Tuncer, I., Unusan, C., & Cobanoglu, C. (2021). Service quality, perceived value and customer satisfaction on behavioral intention in restaurants: an integrated structural model. *Journal of quality assurance in hospitality and tourism*, *22*(4), 447–475. DOI:10.1080/1528008X.2020.1802390

[44] Scheidt, S., & Chung, Q. B. (2019). Making a case for speech analytics to improve customer service quality: Vision, implementation, and evaluation. *International journal of information management*, *45*, 223–232. DOI:10.1016/j.ijinfomgt.2018.01.002

[45] Dam, S. M., & Dam, T. C. (2021). Relationships between Service quality, brand image, customer satisfaction, and customer loyalty. *Journal of asian finance, economics and business*, *8*(3), 585–593. DOI:10.13106/jafeb.2021.vol8.no3.0585

[46] Ingaldi, M., & Ulewicz, R. (2018). Evaluation of quality of the e-commerce service. *International journal of ambient computing and intelligence*, *9*(2), 55–66. DOI:10.4018/IJACI.2018040105

[47] Situmorang, M. J., Ginting, R., & Ishak, A. (2014). Quality function deployment (QFD) method approach to improve hypermarket service quality at XYZ hypermarket. *USU Journal of Industrial Engineering*, *4*(1), 219563. https://garuda.kemdikbud.go.id/documents/detail/1431570

[48] Rottie, R. F. I., Sukapto, P., & Hariandja, J. (2017). Improving the service quality of restaurant X with the integration of DINESERV, ZOT and QFD methods. *Scientific journal of industrial science and technology*, *1*(1), 11–20.

[49] Syukri, & Ainu, S. H. (2014). Application of customer satisfaction index (CSI) and gap analysis on Trans Jogja service quality. *Industrial engineering scientific journal*, *13*(2), 103–111.

[50] Berkes, F. (2017). *Sacred ecology*. Routledge.

[51] Tursch, P., Goldmann, C., & Woll, R. (2015). Integration of TRIZ into quality function deployment. *Management and production engineering review*, *6*(2), 56–62. DOI:10.1515/mper-2015-0017

[52] Novia Jamilatur R, Bayu Wijayantini, H. H. (2019). Penerapan quality function deploymen (QFD) untuk meningkatkan kepuasan pelanggan pada toko butik. *Unhum jember*, 1–14. http://repository.unmuhjember.ac.id/6445/1/ARTIKEL.pdf

[53] Gozaly, J., & Talar, Y. (2021). Analysis of the quality of administrative services for the community (case study: sub-district office in North Bandung). *Industrial engineering journal*, *16*(2). https://doi.org/10.14710/jati.16.2.93-101

[54] Ginting, R., Ishak, A., Malik, A. F., & Satrio, M. R. (2020). *Product development with quality function deployment (qfd): a literature review* [presentation]. IOP conference series: materials science and engineering (Vol. 1003, p. 12022). https://iopscience.iop.org/article/10.1088/1757-899X/1003/1/012022/pdf

[55] Dyana, N., Budiharti, N., & Galuh, H. (2020). Quality function deployment (QFD) analysis for improvement of Kaw-Kaw Brand Thai Tea Products in Franchise UKM in Landungsari, Malang. *Journal valtech*, *3*(2), 153–159.

[56] Nurwulan, F. A., Desrianty, A., & Fitria, L. (2014). Analysis of services at the Dki Jakarta regional drinking water company using the service quality method. *National institute of technology online journal*, *2*(1), 435–447.

[57] Novrianto, J. (2016). Customer satisfaction analysis at Pertam Tunjang soap restaurant (m1) source: pertama Tunjang Sop Restaurant. *Journal valuta*, *2*(2), 171–189.

[58] Ali, B. J., Saleh, P. F., Akoi, S., Abdulrahman, A. A., Muhamed, A. S., Noori, H. N., & Anwar, G. (2021). Impact of service quality on the customer satisfaction: case study at Online meeting platforms. *International journal of engineering, business and management*, *5*(2), 65–77. DOI:10.22161/ijebm.5.2.6

[59] Deyo, R. A. (2000). Quality and its dimensions. *Spine*, *25*(6), 661. DOI:10.1097/00007632-200003150-00002

[60] Martilla, J. A., & James, J. C. (1977). Importance-performance analysis. *Journal of marketing*, *41*(1), 77–79.

[61] Suci, A. (2017). The highest number of micro small enterprises (MSE) in culinary business generates enterpreneur's efforts to gain their service excellence. *IDEAS*, *9*(1), 1832–1840.

[62] Shvetsova, O. A., Park, S. C., & Lee, J. H. (2021). Application of quality function deployment for product design concept selection. *Applied sciences (switzerland)*, *11*(6). DOI:10.3390/app11062681

[63] Milunovic Koprivica, S., & Filipovic, J. (2018). Application of traditional and fuzzy quality function deployment in the product development process. *EMJ - engineering management journal*, *30*(2), 98–107. DOI:10.1080/10429247.2018.1438027

[64] Sanjaykumar R Gangurde, S. S. P. (2018). Benchmark product features using Kano - QFD approach : a case study. *Benchmarking: an international journal*.

[65] Pourkhandani, M. H., & Iranban, S. J. (2014). QFD application using combined ANP-DEMATEL approach for improving service quality: a case study of dental clinic. *Journal of applied research on industrial engineering*, *1*(4), 230–249.

[66] Popoff, A., & Millet, D. (2017). Sustainable life cycle design using constraint satisfaction problems and quality function deployment. *Procedia cirp*, *61*, 75–80. DOI:10.1016/j.procir.2016.11.147

[67] Devnath, A., Islam, M. S., Rashid, S., & Islam , E. (2020). An integrated QFD-TOPSIS method for prioritization of major lean tools: a case study. *International journal of research in industrial engineering*, *9*(1), 65–76. DOI:10.22105/riej.2020.213445.1110

[68] Noriaki, K. (2001). *Life cycle and creation of attractive quality* [presentation]. Proceedings of the 4th qmod conference, linkoping, sweden (pp. 12–14). https://cir.nii.ac.jp/crid/1570291225457377408

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Thermodynamic Analysis of Hybrid-Nanofluids-Zeotropic Mixtures in a Vapour Compression Refrigeration System (VCRS) Based on Exergy Principles

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Abstract

Cooling refrigeration systems ingest prime energy and contribute to universal negative impact due to ecologically unfavorable working fluids used. Hence, the quest to improve the performance of Vapour Compression Refrigeration System (VCRS) with more efficient and eco-friendly refrigerant such as nanoparticles becomes imperative. In this study, performance analysis of hybrid nanofluids-zeotropic mixtures in a VCRS were experimentally investigated to determine the best operating optimum performance using exergy based approach. To achieve this, varying concentrated mixtures were selected using ternary graph. The results revealed that all the designated ratios of the mixed refrigerant with different fractions achieved good performance improvement with optimum values obtained at (011) zero gram of TiO_2, 7.5g-Al_2O_3/CuO. All the selected hybrid mixtures led to an improved outcome in terms of Coefficient of Performance (COP), less power consumption and high performance exergetic efficiency, with COP values ranging from 0.31% to 3.10% and exergetic efficiency from 0.32 to 1.43%. The value for thermal conductivity, dynamic viscosity, density and specific heat were found to be highest (0.0958 W/m.K; 0.00164 W/m.K; 686.82 kg/m^3 and 359.82 kJ/kg.K) at the same concentration of zero grams TiO_2 in the mixture. Comparison made from the performance characteristics curve (with global parameters) indicated that maximum power coefficient and cooling capacity for the various concentrations were found at (001) 7.5g-TiO_2, zero grams Al_2O_3/CuO equal to 2.2 kW, and the minimum value at concentration of 5 was 0.61% at (111) 5g-TiO_2/Al_2O_3/CuO, and 0.87% for (121). An increase was observed in the maximum power coefficient, cooling capacity and COP increased by 13.51%, 5.78% and 10.33%. It was also observed that hybrid nanofluid-zeotropic refrigerant worked seamlessly with VRCS, making it a sustainable, green and clean as well as eco-friendly alternative with near-zero to zero negative effects on public health safety and environment.

Keywords: Nanofluids, Heat transfer coefficient, COP, Exergy efficiency, Exergy destruction.

1 | Introduction

The Advancement in alternative energy resources have paved way for technological innovations towards the augmentation of energy mix, utilization and conversion of alternative energy resources into viable options. Therefore, the physiognomies of the global energy patterns, which is subjugated by relic vigor, have triggered some negative environmental impairment initiated via the use of this energy options. In attempt to find a solution to these problem, alternatives that are economically viable, globally acceptable and ecologically friendly to advance the effectiveness of these energy alternatives is highly required [1]–[3]. The Vapour Compression Refrigeration System (VCRS) remains one of the promising working fluids applicable in refrigeration systems, an energy system that is commonly used for cooling and preserving perishable items [4]. Hence, working fluids that are ecofriendly have become the research hotpots of VCRS in recent times. Working fluids employed

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in the system flows via different transformative phases, interchangeably trodden and expanded from liquescent to vapour. In the process of these transformations, heat is enthralled or exorcised through the system, resulting in temperature variation of the nearby transient air along the system components. Almost all VCRS operates in this sequence to achieve chilling, and the energy expended in the system is relatively high. Prior to the 21st century, refrigerants have always been known to contribute immensely to global warming due to its constituents, some of which are major greenhouse gases [5], [6]. Upon realizing that some of the working fluids are highly combustible and noxious, scientific research by different scientists began to increase in various capacities in order to develop refrigerants that are more ecofriendly.

This led to the development of Chlorofluorocarbon (CFC) in 1930 which was none flammable and toxic as well as cost effective gases that seemed to be a better alternative, but was later observed to contain toxic compounds that were depleting the ozone layer.

As a result of that, Hydrochlorofluorocarbon (HCFC) were developed in the late 70s and early 80s, which were also observed to contain compounds such as chlorine molecules which had more damaging effects on the ozone layer. Furthermore, various attempts to find a sustainable solution to this problem led to the development of HFCs which does not contain chlorine but was later found to contribute to environmental impairment since they are greenhouse gases. From the aforementioned evolutions in the development and application of working fluids for refrigeration systems, refrigerants that existed before the 21st century were obviously depleting the ozone layer and causing Global Warming Potential (GWP), and that necessitating the need for new environmentally friendly refrigerants with excellent heat transfer characteristics [7]. Conversely, selecting an eco-friendly working fluids (refrigerants) presently is an issue of concern, and alternatives available nowadays include zeotropic mixtures (R400 series), hydrocarbons and carbon dioxide (R744).

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McLinden and Huber [8] reported that refrigerants have continually evolved in response to evolving trends due to changes in the type of equipment and their effects on public health safety and environmental requirements. In the late 1920s, it was observed that addition of fluorine to molecules could produce a non-flammable and low toxicity refrigerant, thus giving high preference to the CFCs. During the 1980s, CFCs were observed to contribute to the destruction of stratospheric ozone, thereby, causing undesired environmental issues. From R-12 in the 1930s to R-1234yf in the early 2000s, were reported in the chemical literature, decades before they were considered as refrigerants. The search for new refrigerants continued through the 1990s even as the HFCs were becoming the dominant refrigerants in commercial use.

Studies have shown that research on hybrid-nanofluids-zeotropic mixture in VCRS application is limited, therefore, necessitating the need for alternative working fluids as well as innovative approaches to improve the cooling performance in refrigeration systems. As a result, the choice of using zeotropic mixtures as a refrigerant is becoming a bone of contention regarding the operation of vapour compression systems. In recent times, a number of studies have been conducted on the thermodynamics of hybrid-nanofluids-zeotropic mixtures in a VCRS based on exergy principles.

For example, thermodynamic analysis of VCRS with sustainable refrigerant blends as alternatives to replace R22 was investigated by Talanki and Shaik [9]. Eight (8) refrigerant blends consisting of R290, R134a, R152a, R125 and R32 at various compositions were developed. Performance characteristics of the eight studied refrigerants were computed at evaporating and condensing temperature of 7.2oC and 54.4oC via MATLAB programme. Coefficient of Performance (COP) of the refrigerant mixture RM40 (3.541) was recorded as the highest among the eight studied refrigerants with 0.2% higher than the COP of R22 (3.534). GWP of RM40 (10) was lower than GWP of R22 (1760), and those of the other eight refrigerants. Compressor discharge temperature of RM40 was the lowest among the eight refrigerants with 6.6oC reduction when compared to R22. Power spent per ton of refrigeration of RM40 (0.992 kW/TR) was the lowest among the eight refrigerant mixtures and marginally lower than that of R22

(0.994 kW/TR). Volumetric Cooling Capacity (VCC) of RM40 (2837 kJ/m3) was higher among the eight refrigerants but close to that of R22 (3086 kJ/m3).

The performance of four Al2O3 nano-refrigerants and their pure fluids (R600a, R134a, R1234yf, and R1233zd (E)) was analysed in a VCRS by Li and Lu [10]. The COP improvement of R1233zd (E) + Al2O3 nano-refrigerant was the highest, while the COP improvement of R134a + Al2O3 and R1234yf + Al2O3 were close to one another. When the mass fraction of Al2O3 nanoparticles increased to 0.30%, the COP of R1233zd (E) and R600a also increased by more than 20% with maximum exergy efficiency of 38.46% for R1233zd(E) + Al2O3 and minimum exergy efficiency of 27.06% for pure R1234yf. The findings revealed that the addition of nanoparticles to the pure refrigerant improved the heat transfer in heat exchangers, increased cooling capacity, reduced compressor power consumption, leading to improved performance of the refrigeration system.

Walid Faruque et al. [11] carried out an investigation to find an environmentally friendly refrigerants that can be applied on a Triple Cascade Refrigeration System (TCRS) for low-temperature application (-100oC to -150oC). To assess the performance of TCRS, energy analysis and exergy analysis were conducted, and analysed. The results revealed that 1-butene/heptane/m-Xylene pair gives the best performance in terms of 1st law efficiency COP and 2nd law efficiency (exergy destruction) for low-temperature applications (lower than -100°C). From the simulation model, the results also indicated that exergy destruction mainly occurs at the condenser, therefore, further studies can be carried out on the condenser to increase the overall COP.

In the same vein, Prasad et al. [12] carried out exergy analysis on VCRS based on the second law efficiency. The second law efficiency was observed to decrease with increase in evaporator temperature while COP increased with increase in evaporator temperature. Total exergy losses decreased with increase in evaporator temperature. The second law efficiency also decreased with increase in condenser temperature while COP decreased with increase in condenser temperature. The total exergy losses increased with increase in condenser temperature. The second law efficiency increased with increase in the rate of sub-cooling while COP increased with increase in the rate of sub-cooling. The total exergy losses was observed to decreases with increase in the rate of sub-cooling.

König-Haagen et al. [13] conducted an experimental study on the performance of R404A and R507A refrigerants in a double-stage VCRS with a sub-cooler heat exchanger. It was observed that R404A has a better performance at high evaporator temperature application whereas, R507A is more suitable in low-temperature applications. Flores et al. [14] theoretically investigated the function of a cascade system in an ozone friendly refrigerant pair. The results indicated that COP of the system increased from 0.7851 to 1.232 when the evaporator heat was adjusted from -80 to-50 oC with the other parameters kept constant. However, there was decrease in the COP from 0.9274 to 0.5486 when the condenser temperature increased from 25 to 50 oC respectively.

Also, Yao et al. [15] experimentally compared the performance of HCFC refrigerants such as R22, R123, and R124 with three different HFC refrigerants R417A/R422A/R422D in VCRS. The findings revealed that using R417A, R422A, and R422D refrigerants, discharge temperature of the compressor was less than that of R22; thereby, offering an advantage that exposed the compressor to less thermal stress and extended service life.

In addition, Oyekale et al. [16] applied HFC161 refrigerant in a small scale cooling system as substitute for HFC410A refrigerant. The performance of HFC161, HFC410A, and HFC32 refrigerants were analyzed under nominated working conditions. The theoretical results revealed that the performance of HFC161 was 10% greater than that of HFC32, but 17.8% greater than that of HFC410A. However, the tentative outcomes revealed that the COP of HFC161 was 15% greater than that of HFC410A, and 25% greater than the COP of HFC32. Furthermore, expulsion heat of HFC161 refrigerant was lesser than that of HFC32 and HFC410A.

Balaji et al. [17] carried an experiment to comparatively analyze the performance of R32, R134a, and R512a in a VCRS. From the findings obtained, R32 exhibited unfavorable properties in terms of average pressure and little co-efficient of performance. The best performance was observed when R152a was applied which had a phenomenal potential of being used as direct replacement for R134a in a VCRS. Moreover, 2.5% COP as obtained for R152a was observed to be higher than that of R134a and R32, but 14.7% higher than that of R134a. It was observed that R152a yielded the most favorable outcome in terms of ecofriendly requirements, with specific universal heating potential, among other requirements.

The rationale behind combining nanofluids-zeotropic mixtures in cooling systems is reportedly viable in terms of providing substantial improvement and reduction in energy consumption compared to the early refrigerants developed before the 21st century. This study is aimed at conducting a thermodynamic analysis of hybrid-nanofluids-zeotropic mixtures in a VCRS based on exergy principles. Also, it is limited to evaluating the effects of varied nanofluid-zeotropic composition to determine the best optimum performance on the VCRS.

2 | Materials and Methods

The materials and methods employed in the study are presented in the headings captured under this section.

2.1 | Materials

The experiments were conducted using refrigerator test rig system; blends of nanofluids--zeotropic mixtures (HFC- R407C, $CuO/TiO_2/Al_2O_3$ by weight); product (water); pressure and temperature gauges; glass beaker; mechanical stirrer, gas cylinder, compressor oil, digital electronic weighing balance, among others. The system was designed with the aid of the design theory. Internal cooling capacity of the cabinet was 2208 mm, external capacity of the cabin was 2420 mm, the top/bottom cover of the cabinet was 1104 mm while the total length of the frame was 5732 mm. Other instruments/equipment included: a digital thermometer for temperature sensors measurement ranging from (-10°C-110°C, ±3°C); ankle bar (iron bar), galvanized steel, cork board material, polystyrene, aluminum plate, drilling machine, fan, and connecting wires.

2.2 | Methods

A comprehensive review of literature on VCRS with nanoparticle zeotropic mixtures was thoroughly examined. A model VCRS coupled with external fan and pipe coiled round evaporator were developed. A ternary diagram was used to determine the percentage particles proportional composition for the mixed refrigerant. For the design features/components comprised of two sections: the cabinet chamber and the measuring chamber. The major components included the frame, the body cover, fan, electric switch, condenser, evaporator and compressor motor with specifications according to design capacity of the systems. The advantage of using nanorefrigerants is that they have a greater heat transmission coefficient, which allows an increase the performance of refrigeration systems.

2.2.1 | Preparation/procedure for blending hybrid-nanofluid zeotropic refrigerants

Eleven different samples of ternary blend was done by hybridizing ($Al_2O_3/TiO_2/CuO$ into POE -Poly Ester oil), then subjecting it with zeotropic mixtures of (23% Difluromethane; 25% Pentafluroethane and 52% Tetrafluroethane by weight) to have a blending of hybrid-nanofluid zeotropic refrigerants in HFC as the base fluid. The various weights/mass were determined using a digital electronic weighing balance.

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2.2.2 | Experimental setup

The experiment was conducted using a model VCRS (see *Fig. 1*) as a prime auxiliary for domestic refrigerators. Results obtain was recorded in the data acquisition template which was designed using Microsoft Excel for data processing spread sheet. To achieve this, essential apparatus was positioned at the respective required places. A calibrated temperature sensors (thermometer) were used for temperature reading of the tested product. The flow degree of the mixtures and energy intake of the compressor were analyzed according to *Eqs. (1)* to *(7)*. The analysis was done based on energy and mass stabilities in the entire constituents. *Fig. 1* shows pictorial view of the VCR test rig developed with 25 liter capacity cooling space. Moisture evacuation was done using the installed service ports, and flushed with ammonia gas and further rinsed with the mixture to eliminate remnant of the previous mixture, impurities and other particles in the device. Various samples with different concentrations were measured by digital weighing balance. After flushing, it was turned on, infused by the proper volume fraction through charging line, and monitored within a range of an hour period before taking the (SS) temperature and pressure readings by the inlet and exist of the major component, and product was introduce and monitored at intervals of 15 minutes. The tests were performed to study COP, cooling rate, energy intake, and intervals engaged for product ambient temperature change towards cooling state.

Fig. 1. Vapour compression refrigeration test rig.

2.2.3 | Calculated performance parameters (assumptions made)

The following assumptions were being observed for the analysis of the system: steady-state flow operation is assumed in all the system individual parts; the working fluid has varied percentage composition throughout the cycle; pressure losses along each component are neglected with 75% isentropic proficiency. By applying Stable Stream Drive Equation (SSDE), energy balance mathematical model expression is given by *Eqs. (1)* to *(7)* according to Balaji et al. [17].

Work consumed by the compressor ($\dot{W}_C$) is given according to *Eq. (1)* as:

$$\dot{W}_C = \dot{m}(h_1 - h_2). \tag{1}$$

The work done per kg of refrigerant by the compressor is given as (compressor work input required):

$$W = h_2 - h_1. \tag{2}$$

Heat rejected in the condenser (Q_c) from *Eq. (3)* is thus:

$$Q_c = \dot{m}(h_2 - h_3). \tag{3}$$

For capillary tube (expansion valve);

$$h_3 = h_4. \tag{4}$$

Heat absorbed in the evaporator (Q_e) is given by *Eq. (5)*:

$$Q_e = \dot{m}(h_1 - h_4). \tag{5}$$

VCC is given by *Eq. (6)*:

$$VCC = \frac{\text{Refrigeartion Effect}}{\text{Compressor input specific volume}} = \frac{(h_1 - h_4)}{v_1}. \tag{6}$$

The COP was determined using *Eq. (7)*:

$$COP = \frac{Q_e}{\dot{W}_C}. \tag{7}$$

2.2.4 | Exergy destruction in each parts of the cycle

Exergy destruction in a compressor is given by *Eq. (8)*:

$$I_{comp} = ED_{xd\,1-2} = \dot{m}T_0(\psi_{out} - \psi_{in}) + W_{el} = \dot{m}T_0(S_1 - S_2) + W_{el}. \tag{8}$$

The irreversibility or the exergy loss in condenser is expressed in *Eq. (9)*:

$$I_{dest,cond} = ED_{xd\,2-3} = T_0 S_{gen} = \dot{m}T_0\left(S_3 - S_2 + \frac{q_c}{T_c}\right). \tag{9}$$

Exergy of expansion valve is expressed in *Eq. (10)*:

$$I_{dest,exp} = ED_{xd\,3-4} = T_0 S_{gen} = \dot{m}T_0(S_4 - S_3). \tag{10}$$

Exergy of evaporator is expressed in *Eq. (11)*:

$$I_{dest,evap} = ED_{xd\,4-1} = \dot{m}T_0\left(S_1 - S_4 - \frac{q_{Evap}}{T_{Evap}}\right). \tag{11}$$

The total exergy destruction rate ($\dot{X}_{Total}$) is given by *Eq. (12)*:

$$\dot{X}_{Total} = (ED_{xd\,total}) = ED_{xd\,1-2} + ED_{xd\,2-3} + ED_{xd\,3-4} + ED_{xd\,4-1}. \tag{12}$$

Second law efficiency of the system according to ketan Nayak et al. [18] is the ratio of exergy output (X_{output}) to exergy input (X_{input}) given as thus:

$$\eta_{exergetic} = \frac{\text{Exergy output}}{\text{Exergy input}}. \tag{13}$$

$$\eta_{exergetic} = \left[\frac{X_{output}}{X_{input}}\right] \times 100\%. \tag{14}$$

$$X_{output} = X_{input} - X_{total}. \tag{15}$$

Where $\eta_{exergetic}$ (see *Eq. (16)*) is the exergy efficiency of the whole actual VCS, and exergy input to the system is supplied through the compressor work. This implies that $X_{input} = \dot{W}_c$.

$$\eta_{exergetic} = \left[1 - \frac{X_{total}}{\dot{W}_c}\right] \times 100\%. \tag{16}$$

3 | Results and Discussion

This section shows the results obtained during experimental investigation. Exergy destruction in each part of the cycle based the relation in *Eqs. (1)* to *(16)* was collated in *Table 1* which correlates with the results of ketan Nayak et al. [18] and Abhishek and Gupta [19].

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Table 1. Calculated values of exergy destruction in each component at various % fractions.

Particles Concentration (%)	Compressor (kW)	Condenser (kW)	Expansion Valve (kW)	Evaporator (kW)	Total Exergy Destruction	Mean Cooling Time (S)	R_E	W_c (kJ/kg)	$\eta_{exergetic}$ (%)	$\dot{m}$(kg/s)	COP	Power Consumption (kW)
(001)	3.283	68.46	44.41	-2.415	111.54	19.5	3.1	2.048	0.54	0.225	0.53	2.199
(010)	1.062	45.77	40.62	-0.651	86.71	18	2.3	1.132	0.76	0.222	0.45	1.216
(100)	1.394	47.96	42.66	-1.129	90.89	12.5	3.6	1.229	0.73	0.236	0.69	1.319
(011)	41.99	48.48	44.72	-9.369	125.82	14	12.1	0.888	1.43	0.225	3.10	0.942
(111)	1.332	46.15	40.76	-1.059	39.73	18	3.5	0.648	0.32	0.224	1.21	0.696
(211)	1.071	51.67	45.31	-0.663	97.39	20	2.3	1.040	0.94	0.226	0.50	1.117
(121)	0.671	41.43	36.83	0.248	78.57	17	1.2	0.806	0.97	0.207	0.31	0.866
(112)	0.839	48.85	43.87	0.937	94.41	15.5	6.5	1.006	0.93	0.219	1.41	1.081
(221)	1.395	40.32	43.98	0.964	84.11	15.5	5.7	1.488	0.57	0.216	0.83	1.598
(212)	1.454	39.63	43.86	1.266	82.71	14.5	8.7	1.497	0.55	0.214	0.59	1.608
(122)	1.550	45.31	41.86	1.525	90.25	14	3.0	0.881	1.02	0.210	0.71	0,955

3.1 | Mass Flow Rate

Fig. 2 illustrates the plot of measured mass flow rate as a function of nanoparticle zeotropic mixtures volume fraction of a VCR cooling system working with eleven different concentration ratios ranging from 3.0 to 15.0g bulk fluid control having a mass flow rate between 0.207 to 0.236 (kg/s). Conversely, higher performance was obtain between (100) 15g- CuO, zero gram of Al_2O_3/TiO_2 and (211) 7.5-TiO_2; 3.75-Al_2O_3/CuO concentration ratio (refrigerant) charge with optimum mass flow rate of 0.236 (kg/s) and 0.226 kg/s, greater than (121) and (112)% fraction with six based optimum mass volume fraction as tabulated in *Table 1*. Cooling result of the system was boosted due to increase in mass composition as observed with those obtained by Oyewola et al. [20].

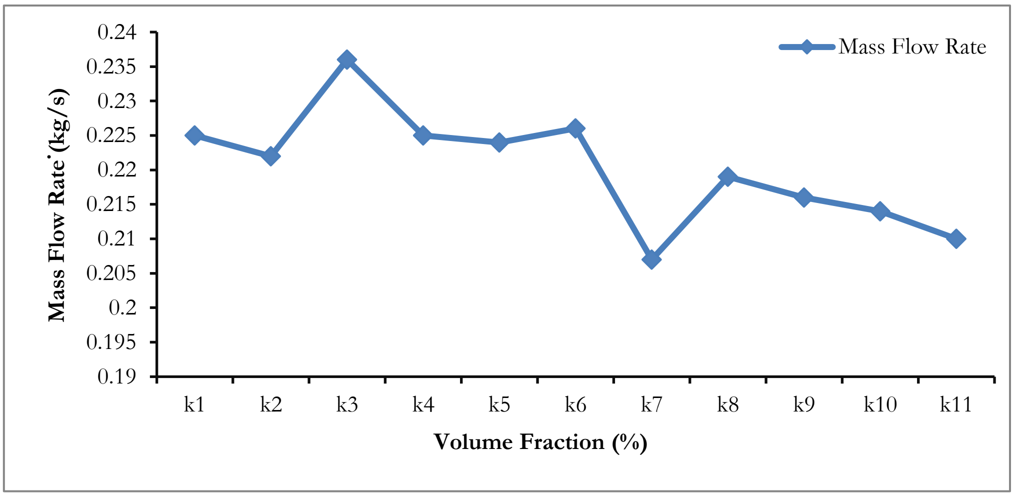

Fig. 2. Plot of mass flow rate versus volume fraction.

3.2 | Compressor Power Consumption (kW)

Fig. 3 shows a plot of compressor power consumption as a function of nanoparticle zeotropic mixture volume fraction. The fig indicates that decrease in energy feedback to the compressor increases the COP and drops the evaporator temperature of the system. The experimental survey clearly show that four different ratio composition in the other of (0.942, 0.696, 0.866 and 0.955 kW) produced the base lower power output that were (011) zero gram-TiO_2; 7.5g-Al_2O_3/CuO; (111) 5.0g-TiO_2/Al_2O_3/CuO; (121)

3.75g-TiO_2/CuO, 7.5g-Al_2O_3 and (122) 3.0g-TiO_2, 6.0g-Al_2O_3/CuO, but obtained the highest power output of 2.199 kW at the ratio of (001) 15.0g-TiO_2, and zero gram-Al_2O_3/CuO. It was further observed that the hybridization of nanofluid-zeotropic mixtures of TiO_2/Al_2O_3/CuO with a less volume fraction and evaporation temperature had the capacity of lowering power consumptions in a refrigeration system from 2.199 kW to 0.696 kW when compared with pure LPG refrigerants which yielded the highest consumption power of 73.20 kW as reported in literature. However, in the study conducted by Bi et al. [21], using R134a refrigerant with TiO_2/SiO_2 lubricant, the power consumption rate increased to about 23.5 kW compared to that of the current study which brought about reduction in the energy consumption.

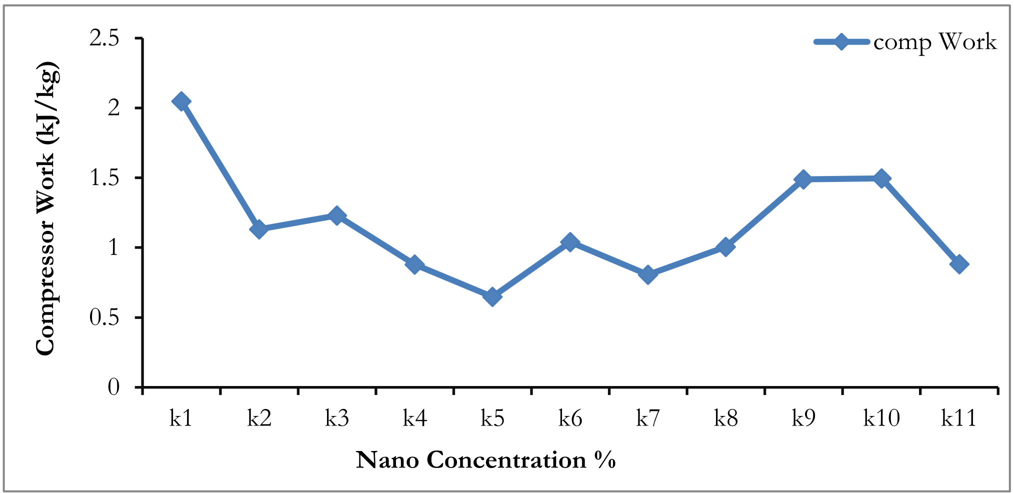

Fig. 3. Plot of compressor power consumption versus volume fraction.

3.3 | Refrigerating Effect

Fig. 4 illustrates the distinction of Refrigerating Effect (RE) and volume fraction cooling outcome through vaporizing temperature from -11°C to -5°C at 16°C condensation temperature. The fig revealed that cooling outcome of the system increased when the vaporizing temperature decreased from (001) 15g-TiO_2, zero gram-Al_2O_3/CuO with 3.1 to 1.2 kJ/kg, having an optimum operating system of 12.1kJ/kg under volume fraction of (011) with zero gram of -TiO_2 and 15g of -Al_2O_3/ CuO. From the aforementioned, the RE of the system increased when the volume fraction decreased. Bolaji et al. [17] and Mohanraj et al. [22] had similar refrigeration output and power coefficient which agrees with the findings of this study.

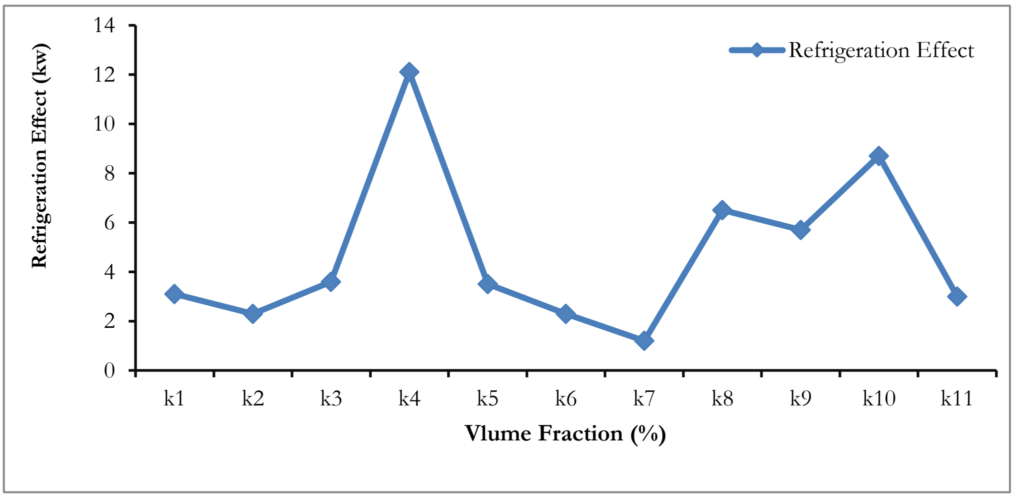

Fig. 4. Plot of RE versus volume fraction.

3.4 | The Volumetric Cooling Capacity

Fig. 5 demonstrates the distinction between VCC and volume fraction for the various mixture concentrations of nanofluid-zeotropic refrigerants. The zigzag trend of the plot shows the refrigeration effect per unit volume of vapor entering the compressor with a decrease in evaporator temperature. This is due to particles size concentration of each mixture, which implies that the greater the VCC, the lesser the compressor power consumption required. Results obtain revealed three optimum volume fraction at (011) zero gram-TiO_2, 7.5g-Al_2O_3/CuO having 68.03 (kJ/m^3), followed by (121) 3.75g-TiO_2/CuO, 7.5g-Al_2O_3 with 67.03 (kJ/m^3) and (212) 6.0g-TiO_2/CuO, 3.0g- Al_2O_3 having 48.84 (kJ/m^3). Other possible combination to be considered were (112) 3.75g-TiO_2/ Al_2O_3, 7.5g- /CuO; (221) 6.0g-TiO_2/ Al_2O_3, 3.0g-CuO with 37.03 and 32.01 (kJ/m^3).

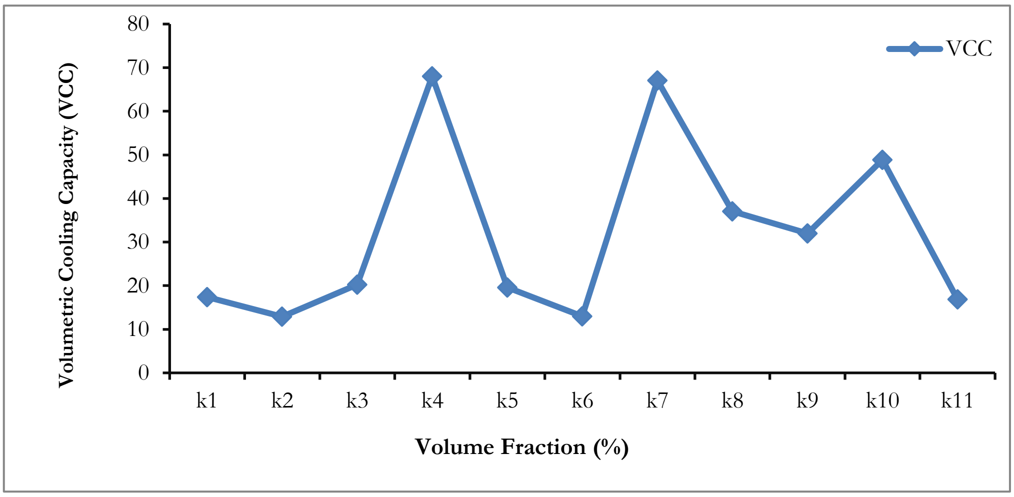

Fig. 5. Plot of variation of VCC versus volume fraction.

3.5 | Coefficient of Performance

Fig. 6 describes the COP as a function of volume fraction. It is found that the COP increased with varied volume fraction ratios and increased as the evaporation temperature (T_{evap}) decreased for the condensation temperature ranging from 11 to 16 ^{0}C, having the optimum COP of 3.1% at particles combination of (011) as also observed in *Fig. 5*. This implies that volume fraction of (011) is a desirable refrigerant mixture alternative, followed by (211) with 0.83%, (112) with 0.71% and (100) with 0.69%. COP of 2.06% was observed from the study conducted by König-Haagen et al. [13], Flores et al. [14] and Dossat and Horan [23] with SiO_2 and TiO_2 established oils with both having COP of 2.97.

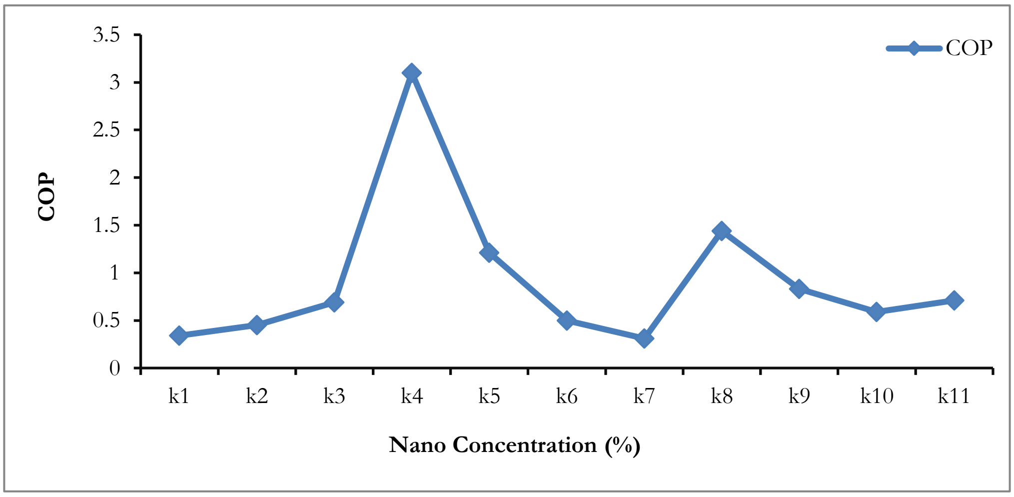

Fig. 6. Plot of COP versus volume fraction.

3.6 | Exergy Destruction Ratio in the System Components

Fig. 7 shows variation of individual system components versus volume fraction. Experimental data obtained from the test rig agreed with the findings of other researchers such as Adelekan et al. [24], Ohunakin et al. [25], Sajid and Ali [26] and many others, confirming that to specify the exergy losses or destructions in the system, exergy analysis is necessary. The result revealed that maximum exergy damage value is obtain via the condenser with 68.46 kW at volume fraction of (001), with 7.5g-TiO_2, zero gram-Al_2O_3/CuO, followed by (211), 7.5g-TiO_2, 3.75g-Al_2O_3/CuO with 51.67 kW and (112), (011) and (100) with 48.85, 48.48 and 47.96 kW. The second highest exegetic loss is observed in expansion valve at (211) and (011) with 45.31 and 44.72 kW. The next loss is found in compressor at (011) with 41.99 kW and subsequently followed by evaporator at (011) with -9.37 Kw. The survey indicated that optimum cooling rate in the evaporator is at volume fraction of (011) zero gram-TiO_2, 15g-Al_2O_3/CuO with the compressor efficiency showing maximum performance at the same volume fraction of (011) with 41.99 kW. The variation in individual components is at the increase, based on nanofluid porosity and size. As compared with work done by others researchers, it was observed that nano-zeotropic mix has the ability to stabilize vapour compression system with less power consumption as in agreement with those obtained by Mohanraj et al. [22], Padilla et al. [27] and Ziegler and Alefeld [28].

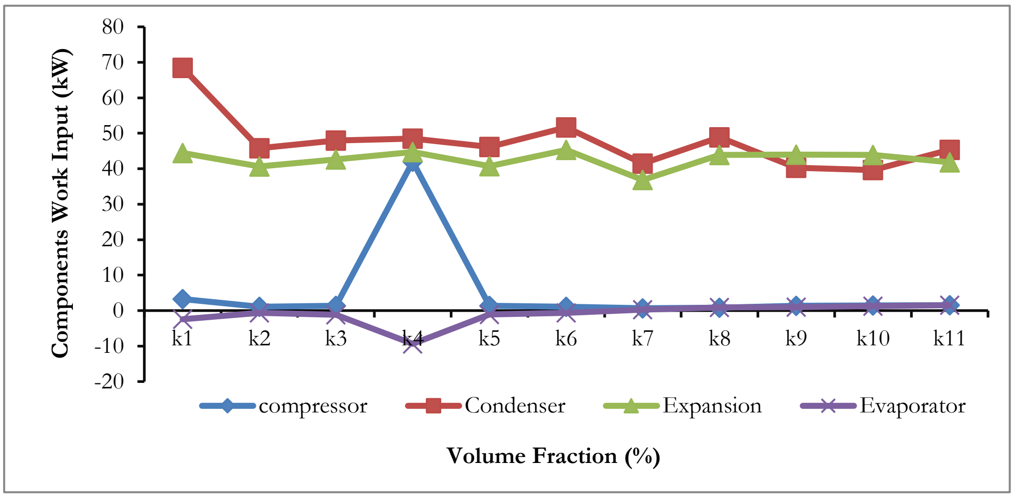

Fig. 7. Variation of individual system components versus volume fraction.

4 | Conclusions

In this work, the thermodynamic analysis of hybrid-nanofluids-zeotropic mixtures in a VCRS based on exergy principles was experimentally investigated. Measurements of the global parameters (compressor power consumption, cooling time, VCC, refrigeration effect, mass flow rate, condenser, exergy damage ratio in each component, heat transfer rate, among others) were investigated. The results showed different effects that each concentration had on these parameters based on the individual concentrations mixtures. It further revealed that (011) zero gram-TiO_2, 7.5 g-Al_2O_3/CuO and (112) 3.75 g-TiO_2/Al_2O_3, 7.5 g-/CuO–concentration mixtures enhanced the demonstration of the cooling process with better efficiency and maximum COP in all phases of measured measurements done in this study. The study indicated that (111) 5 g-TiO_2/Al_2O_3/CuO with 0.65% showed the lowest compressor work with low GWP value whereas, characterization tests conducted revealed that the hybrid-refrigerant shows optimistic influence on the energy intake capacity. Comparisons made shows that maximum power coefficient and cooling capacity for the eleven different volume concentrations was found at (001) 15 g-TiO_2, zero gram-Al_2O_3/CuO equal to 2.2 kW, and the minimum value of power coefficient at concentration 5 remained establish in the direction equal to 0.61% at (111) 5 g-TiO_2/Al_2O_3/CuO, and 0.87% for (121). Hence, the maximum power coefficient, cooling capacity, and COP increased by 13.51%, 5.78%, and 10.33% respectively. This implies that nanoparticles can significantly improve the power output and cooling capacity even in a low volume concentration and complex system. From the analysis carried out in this study, further analysis is recommended for determining the anti-wear characteristics of the hybrid nanofluid-zeotropic mixtures to establish the dependability of its use in a VRCS. Moreover, considering the effects of nanofluid-zeotropic mixture refrigerant on public health safety and environment, permissible refrigerant control, wellbeing standard and codes should be taken into consideration.

References

[1] Aniekan, I. K. P. E., Ebunilo, P., & Okovido, J. (2018). Investigation of the energy (biogas) production from co-digestion of organic waste materials. *International journal of energy applications and technologies*, *5*(2), 68–75.

[2] Aniekan, I. K. P. E., Imonitie, D. İ., & Akanu-ibiam, E. (2019). Investigation of the energy (biogas) derivation from anaerobic digestion of food waste products. *Academic platform-journal of engineering and science*, *7*(2), 332–340.

[3] Nosa, A. G. H. O., Aniekan, I. K. P. E., Sadjere, G., & Tamuno, R. (2018). Evaluation of the energy potential of cow dung in microbial fuel cell for micro-power applications in Nigeria. *International journal of energy applications and technologies*, *5*(2), 98–106.

[4] Owunna, I. B., Ikpe, A. E., Satope, P. O., & Sangotayo, E. O. (2018). A preliminary investigation of solar powered vaccine refrigerator for use in rural hospitals in Nigeria. *University of benin journal of science and technology*, *6*, 31–43. https://unibenjournal.org/publications/preliminary-investigation-solar-powered-vaccine-refrigerator-use-rural-hospitals-nigeria

[5] Imre, A. R., Kustán, R., & Groniewsky, A. (2019). Thermodynamic selection of the optimal working fluid for organic rankine cycles. *Energies*, *12*(10), 2028. https://doi.org/10.3390/en12102028

[6] Zhang, X., He, M., & Wang, J. (2014). A new method used to evaluate organic working fluids. *Energy*, *67*, 363–369. https://doi.org/10.1016/j.energy.2014.01.030

[7] Sajadi, A. R., & Kazemi, M. H. (2011). Investigation of turbulent convective heat transfer and pressure drop of TiO2/water nanofluid in circular tube. *International communications in heat and mass transfer*, *38*(10), 1474–1478. DOI:https://doi.org/10.1016/j.icheatmasstransfer.2011.07.007

[8] McLinden, M. O., & Huber, M. L. (2020). (R) Evolution of refrigerants. *Journal of chemical & engineering data*, *65*(9), 4176–4193. DOI:10.1021/acs.jced.0c00338

[9] Talanki, A. B. P. S., & Shaik, S. V. (2018). *Thermodynamic analysis of vapour compression refrigeration system with sustainable refrigerant blends as alternatives to replace R22* [presentation]. International refrigeration and air conditioning conference (pp. 1–16). https://docs.lib.purdue.edu/iracc/1939/

[10] Li, S., & Lu, J. (2022). A theoretical comparative study of vapor-compression refrigeration cycle using Al2O3 nanoparticle with low-GWP refrigerants. *Entropy*, *24*(12), 1820. https://doi.org/10.3390/e24121820

[11] Walid Faruque, M., Hafiz Nabil, M., Raihan Uddin, M., Monjurul Ehsan, M., & Salehin, S. (2022). Thermodynamic assessment of a triple cascade refrigeration system utilizing hydrocarbon refrigerants for ultra-low temperature applications. *Energy conversion and management: x*, *14*, 100207. https://doi.org/10.1016/j.ecmx.2022.100207

[12] Prasad, T. H., Reddy, K. P., & Reddy, D. R. R. (2009). Exergy analysis of vapour compression refrigeration. *International journal of applied engineering research*, *4*(12), 2505-2526.

[13] König-Haagen, A., Höhlein, S., & Brüggemann, D. (2020). Detailed exergetic analysis of a packed bed thermal energy storage unit in combination with an organic rankine cycle. *Applied thermal engineering*, *165*, 114583. https://doi.org/10.1016/j.applthermaleng.2019.114583

[14] Flores, R. A., Aviña Jiménez, H. M., González, E. P., & González Uribe, L. A. (2020). Aerothermodynamic design of 10 kW radial inflow turbine for an organic flashing cycle using low-enthalpy resources. *Journal of cleaner production*, *251*, 119713. https://doi.org/10.1016/j.jclepro.2019.119713

[15] Yao, Y., Li, W., & Hu, Y. (2020). Modeling and performance investigation on the counter-flow ultrasonic atomization liquid desiccant regenerator. *Applied thermal engineering*, *165*, 114573. https://doi.org/10.1016/j.applthermaleng.2019.114573

[16] Oyekale, J., Heberle, F., Petrollese, M., Brüggemann, D., & Cau, G. (2020). Thermo-economic evaluation of actively selected siloxane mixtures in a hybrid solar-biomass organic rankine cycle power plant. *Applied thermal engineering*, *165*, 114607. https://doi.org/10.1016/j.applthermaleng.2019.114607

[17] Balaji, N., Kumar, P. S. M., Velraj, R., & Kulasekharan, N. (2015). Experimental investigations on the improvement of an air conditioning system with a nanofluid-based intercooler. *Arabian journal for science and engineering*, *40*, 1681–1693.

[18] ketan Nayak, A., Hagishima, A., & Tanimoto, J. (2020). A simplified numerical model for evaporative cooling by water spray over roof surfaces. *Applied thermal engineering*, *165*, 114514. https://doi.org/10.1016/j.applthermaleng.2019.114514

[19] Abhishek, T. & Gupta, C. R. (2011). Performance of domestic refrigerator using R-404A to replace R-134A. *International journal of current research and review, 3*(8), 158-163.

[20] Oyewola, O. M., Ajayi, O. O., Katende, J., & Olayinka Oyedepo, S. (2017). A comparative experimental study on performance of domestic refrigerator using R600a and LPG with varying refrigerant charge and capillary tube length. *International journal of energy for a clean environment, 18*(4), 287-302.

[21] Bi, S., Shi, L., & Zhang, L. (2007). Performance study of a domestic refrigerator using R134a/mineral oil/nano-TiO2 as working fluid. *Applied thermal engineering*, *52*(1), 733–737.

[22] Mohanraj, M., Jayaraj, S., Muraleedharan, C., & Chandrasekar, P. (2009). Experimental investigation of R290/R600a mixture as an alternative to R134a in a domestic refrigerator. *International journal of thermal sciences*, *48*(5), 1036–1042.

[23] Dossat, R. J., & Horan, T. J. (2016). *Principles of refrigeration*. Pearson.

[24] Adelekan, D. S., Ohunakin, O. S., Babarinde, T. O., Odunfa, M. K., Leramo, R. O., Oyedepo, S. O., & Badejo, D. C. (2017). Experimental performance of LPG refrigerant charges with varied concentration of TiO2 nano-lubricants in a domestic refrigerator. *Case studies in thermal engineering*, *9*, 55–61. https://doi.org/10.1016/j.csite.2016.12.002

[25] Ohunakin, O. S., Adelekan, D. S., Babarinde, T. O., Leramo, R. O., Abam, F. I., & Diarra, C. D. (2017). Experimental investigation of TiO2-, SiO2- and Al2O3-lubricants for a domestic refrigerator system using LPG as working fluid. *Applied thermal engineering*, *127*, 1469–1477.

[26] Sajid, M. U., & Ali, H. M. (2019). Recent advances in application of nanofluids in heat transfer devices: a critical review. *Renewable and sustainable energy reviews*, *103*, 556–592.

[27] Padilla, M., Revellin, R., & Bonjour, J. (2010). Exergy analysis of R413A as replacement of R12 in a domestic refrigeration system. *Energy conversion and management*, *51*(11), 2195–2201.

[28] Ziegler, F., & Alefeld, G. (1987). Coefficient of performance of multistage absorption cycles. *International journal of refrigeration*, *10*(5), 285–295. https://doi.org/10.1016/0140-7007(87)90073-9

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The Utilization of MARCOS Method for Different Engineering Applications: a Comparative Study

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Abstract

Multiple Criteria Decision Making (MCDM) methods are used widely by researchers to make decisions in the presence of numerous criteria. It is essential to make the right decision for the most of engineering applications which makes the decision-making process more complex and requires further analysis. A major issue of MCDM methods that they suffer from the Rank Reversal Phenomenon (RRP). Another drawback to MCDM methods that they produce different ranking when evaluating the same problem. Thus, researchers tend to develop new methods to overcome these problems. This paper explores the applicability of a new MCDM approach namely Measurement Alternatives and Ranking according to Compromise Solution (MARCOS) by solving four different engineering problems. The results of MARCOS method are analyzed throughout a comparison with the results of other MCDM methods. The rank reversal test is explored for each problem to check the robustness of the method. The two phases of analysis indicate that the method is robust and applicable for different types of engineering applications.

Keywords: Multiple criteria decision making, Rank reversal phenomenon, Measurement alternatives and ranking according to compromise solution method, Comparative study.

1 | Introduction

Multiple Criteria Decision Making (MCDM) is the most well-known branch of decision making, generally Operations Research (OR), which refers to making decisions under multiple, usually complex, criteria [1]. The main target of OR is to improve the decision-making process by providing mathematical tools of analysis, modelling and optimization that help in making better decisions. The MCDM science deals with mathematical theories and methods during the implementation of the decision-making process where multiple criteria are considered through the decision process. The MCDM science resulted from an interdisciplinary background, combining several branches like engineering, economics, computer science and for sure the most used branch in multiple criteria analysis, mathematics. MCDM has changed alongside OR since the early seventies becoming a very important approach in the decision-making processes.

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Through its evolution process, MCDM has changed from “a conceptual-theoretical enterprise of interests practiced by a limited number of disciplines and individuals to a universally embraced philosophy” [2]. Furthermore, MCDM has changed its pattern to give voice to the Decision Maker (DM), as searching for the optimal solution is not required anymore but a solution that satisfies the DM [3].

No matter where the decision-making problems appear, they usually fall under four important categories including selection, ranking, sorting and elimination problems. Since the main use of MCDM methods is to select the best from a set of alternatives or options by considering multiple criteria, the performance of alternatives is measured relative to the set of criteria chosen by the DMs to construct the decision model followed by applying a MCDM approach. The measured data either quantitative or qualitative may have some errors due to the dynamic environment. As a result, MCDM methods produces different rankings when moving from approach to another one, especially when dealing with linguistic terms. The translation of linguistic terms into numerical data is also a complex process that contains uncertainty. Voogd [4] claimed that each MCDM method produces different ranking from the other ones at least 40% of time. Another shortage to MCDM methods is the Rank Reversal Phenomenon (RRP). The RRP refers to a change in the ranking of the alternatives that are previously ranked due to the addition or removal of an alternative from the group already ranked. Most of MCDM methods are supposed to RRP. Thus, several modifications in the mathematical models are done by researchers to overcome the RRP [5]. The occurrence of RRP in a decision-making problem when adding or removing an irrelevant alternative, is clearly conflicts the principle of independence between the alternatives.

The shortages in MCDM methods were an incentive for the researchers to evolve new methods to overcome the drawbacks subjected to the classical models. The most common classical methods in the MCDM science are Analytical Hierarchical Process (AHP) [6], the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [7], Grey Relational Analysis (GRA) [8], The Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) family [9], the Elimination And Choice Translating Reality (ELECTRE) family [10] and the Weighted Sum Model (WSM) [11]. The newly developed methods may include Combined Compromise Solution (CoCoSo) method [12], Ranking of Alternatives through Functional mapping of criterion sub-intervals into a Single Interval (RAFSI) method [13], multi-normalization multi-distance assessment (TRUST) method [14], Logarithm Methodology of Additive Weights (LMAW) method [15] and Measurement Alternatives and Ranking according to Compromise Solution (MARCOS) method [16]. The aim of developing new methods is to improve the decision-making process by overcome the limitations of the classical approaches. However, the new methods need to be investigated for their applicability of providing efficient decision-making process.

There are several studies that investigated the applicability of the MCDM methods through different applications. The Weighted Aggregated Sum Product Assessment (WASPAS) method which is literally a combination of two methods namely WSM and Weighted Product Method (WPM), had been proved to be an efficient MCDM method by solving different engineering problems [17]. The Multi-Objective Optimization method by Ratio Analysis (MOORA) method was used to solve different problems in manufacturing environment [18]. The MOORA had been proven to be simple and robust MCDM method through the comparative study. The reliability of CoCoSo method was investigated through a comparison with different MCDM methods for solving facility location problem [19]. The newly developed methods were not used widely in the engineering applications. Moreover, the MARCOS method was frequently used to solve the supplier selection problem. Stević et al. [16] evaluated a supplier selection problem in healthcare industries and compared their results with six MCDM methods which totally agreed with MARCOS method except for TOPSIS method. The supplier selection problem in a steel industry was addressed by D-MARCOS approach [20] and grey-MARCOS approach [21]. Both hybrid approaches proved the reliability of MARCOS method to handle the uncertainty in information and deal with qualitative attributes. Furthermore, MARCOS method was used for evaluating human resources problem [22], road traffic risk analysis problem [23] and location selection for healthcare waste

[24]. Since the MARCOS method needs a method for assigning the weights for attributes, the Step-wise Weight Assessment Ratio Analysis (SWARA) method was used alongside MARCOS method for inventory classification problem [25]. The integrated AHP-MARCOS was used for the evaluation of renewable energy sources in Turkey [26]. The authors compared their results with other MCDM methods which stated that the best and worst selections were the same for the other methods. Accordingly, the MARCOS method is used in this research to solve different engineering problems due to its simple computational steps compared to the other newly developed methods. The MARCOS method has different integrations with other approaches such as fuzzy sets, grey number and rough sets theory, whereas the raw version of MARCOS method is used in this research to prove its robustness and reliability.

The remainder of this research is organized as follows: Section 2 provides the mathematical procedures of MARCOS method. Section 3 illustrates the numerical examples concerning the selection of industrial robot, gear material, layout design and side-loading forklift. The four examples are solved using MARCOS method and the RRP is explored for each example. Section 4 provides the drawn conclusions from the current research and provides suggestions for future research.

2 | MARCOS Method

The MARCOS method depends on the relation between the alternative's score and the reference values (ideal and anti-ideal solution). Based on this relation, the utility function is calculated and the compromise solution is obtained. The following are the steps of the MARCOS method:

Step 1. Construct the decision-making matrix [D] which indicates the performance of alternatives relatives to the set of chosen criteria.

$$D = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2j} & x_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} & x_{in} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mj} & x_{mn} \end{bmatrix}_{m\times n}.$$

The rows stand for alternatives and the columns stand for criteria, $i = 1, 2, \dots, m$ and $j = 1, 2, \dots, n$.

Step 2. Determine the ideal solution for each criterion (x_{ai}) in the decision-making matrix as follows:

$$D = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2j} & x_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} & x_{in} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mj} & x_{mn} \\ \mathbf{x_{ai1}} & \mathbf{x_{ai2}} & \cdots & \mathbf{x_{aij}} & \mathbf{x_{ain}} \end{bmatrix}_{m\times n},$$

where $x_{ai} = \{\max_j x_{ij}\,;\ j \in \mathscr{B} \ \text{ or } \min_j x_{ij}\,;\ j \in \mathbb{C}\}$.

Step 3. Normalization of the decision-making matrix through *Eqs. (1)* and *(2)*.

$$r_{ij} = \frac{x_{ij}}{x_{ai}}. \tag{1}$$

$$r_{ij} = \frac{x_{ai}}{x_{ij}}. \tag{2}$$

Step 4. Determination of the weighted normalized matrix using *Eq. (3)*.

$$v_{ij} = w_j \times r_{ij}\,. \tag{3}$$

Step 5. Calculate the utility degrees for each alternative (K_i) using *Eqs. (4)* and *(5)*.

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$$K_i^+ = \frac{S_i}{S_{ai}}. \tag{4}$$

$$K_i^- = \frac{S_i}{S_{aai}}, \tag{5}$$

where S_i is the sum of row elements in the weighted normalized matrix ($S_i = \sum_{j=1}^{n} v_{ij}$), S_{ai} is the sum of the ideal solutions in the weighted normalized matrix and S_{aai} is the sum of the anti-ideal solutions in the weighted normalized matrix.

Step 6. Calculation of the utility function in relation to the ideal solution $f(K_i^+)$ and the utility function in relation to the anti-ideal solution $f(K_i^-)$.

$$f(K_i^+) = \frac{K_i^-}{K_i^+ + K_i^-}. \tag{6}$$

$$f(K_i^-) = \frac{K_i^+}{K_i^+ + K_i^-}. \tag{7}$$

Step 7. Determination of the utility function of the alternatives using:

$$f(K_i) = \frac{K_i^+ + K_i^-}{1 + \frac{1 - f(K_i^+)}{f(K_i^+)} + \frac{1 - f(K_i^-)}{f(K_i^-)}}. \tag{8}$$

Step 8. Ranking of the alternatives based on the utility function values. The higher the utility function the more preferred the alternative.

3 | Numerical Examples and Discussion

In this section, the applicability of MARCOS method to solve different types of engineering problems will be discussed through four different examples. The utility function and the related ranking for each alternative will be illustrated for each example. The ranking provided from MARCOS method will be compared to the ranking developed by different methods through the past researches. The rank reversal test will be discussed for each example to review the robustness of MARCOS method. The RRP will be investigated in MARCOS method by the removal of irrelevant alternatives. The lowest ranked alternative is removed at first and the ranking is observed. When the lowest ranked alternative is removed, the ranking either change if the method suffers from RRP or remains in the same order. The series continues until there is only one alternative, the ranked first alternatives. The following are the cited numerical examples in time order. The calculations for each example and the rank reversal tests are done using MATLAB software.

3.1 | Industrial Robot Selection

In this example, the selection of the best industrial robot for pick-n-place operation is discussed. Bhangale et al. [27] aimed to select the best industrial robot among seven candidate robots while five criteria are considered. The criteria are load capacity (C_1), repeatability (C_2), maximum tip speed (C_3), memory capacity (C_4) and manipulator reach (C_5). Among the five criteria, only repeatability (C_2) is non-beneficial attribute. The numerical data for this example are shown in *Table 1*. Bhangale et al. [27] employed TOPSIS method to rank the industrial robots while calculated the criteria weights from relative importance matrix. The criteria weights were found to be completely inconsistent as Rao [28] recalculated the weights of criteria as $w_1 = 0.036$, $w_2 = 0.192$, $w_3 = 0.326$, $w_4 = 0.326$ and $w_5 = 0.120$. The same example was solved by two methods namely, Graph Theory and Matrix Approach (GTMA) and AHP method [28]. The ranking from MARCOS method and the reference methods are shown in *Table 2* where $Rank_G$ and $Rank_A$ refers to the ranking from GTMA and AHP respectively. The rank reversal test for this example is shown in *Fig. 1* which indicates that the method does not suffer from RRP.

Table 1. The data set for industrial robot selection [27].

Alter.	Criteria C_1	C_2	C_3	C_4	C_5
A_1	60	0.4	2540	500	990
A_2	6.35	0.15	1016	3000	1041
A_3	6.8	0.1	1727.2	1500	1676
A_4	10	0.2	1000	2000	965
A_5	2.5	0.1	560	500	915
A_6	4.5	0.08	1016	350	508
A_7	3	0.1	1778	1000	920

Table 2. The ranking of MARCOS method and ref. methods for industrial robots.

Alter.	MARCOS Method		Ref. Methods	
	$f(K_i)$	Rank	$Rank_G$	$Rank_A$
A_1	0.5107	4	2	4
A_2	0.6190	2	3	2
A_3	0.6435	1	1	1
A_4	0.4835	5	5	5
A_5	0.3370	7	7	7
A_6	0.3882	6	6	6
A_7	0.5423	3	4	3
r_s	-	-	0.89	1.00

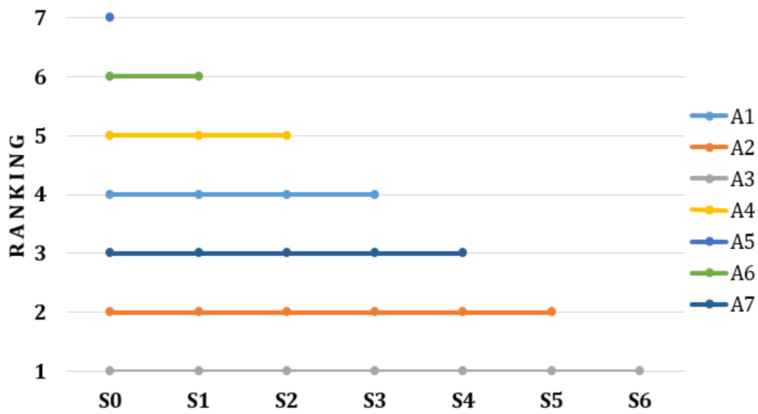

Fig. 1. The rank reversal test for robot selection problem.

3.2 | Material Selection Problem

The applicability of MARCOS method for material selection problem can be investigated by solving the problem of Milani et al. [29] who used TOPSIS method for solving a problem addressing the selection of the best gear material for a power transmission system. They picked up nine candidate materials to rank them relative to set of five criteria. The criteria are tooth surface hardness (C_1), tooth core hardness (C_2), surface fatigue (C_3), bending fatigue limit (C_4) and ultimate tensile strength (C_5). Among the five criteria, only tooth core hardness (C_2) is non-beneficial attribute. The authors used entropy method to assign the weights of criteria which is calculated as w_1 = 0.172, w_2 = 0.005, w_3 = 0.426, w_4 = 0.292 and w_5 = 0.102. The same problem was later solved using preferential ranking methods and the ranking was compared to both VIKOR and PROMETHEE methods [30]. The results of TOPSIS, VIKOR and PROMETHEE will be adopted in the comparison scale for MARCOS method. The data set for this example are shown in *Table 3*. The ranking provided from MARCOS method and reference methods are shown in *Table 4* where $Rank_T$, $Rank_V$ and $Rank_P$ refers to the ranking from TOPSIS, VIKOR and PROMETHEE respectively. The removal of irrelevant alternatives in the ranking of MARCOS method is shown in *Fig. 2* which does not affect the ranking. Hence, the method is stable regarding RRP.

Table 3. The data set for gear material selection [29].

Alter.	Criteria C_1	C_2	C_3	C_4	C_5
A_1	200	200	330	100	380
A_2	220	220	460	360	880
A_3	240	240	550	340	845
A_4	270	270	630	435	590
A_5	270	270	670	540	1190
A_6	585	240	1160	680	1580
A_7	700	315	1500	920	2300
A_8	750	315	1250	760	1250
A_9	185	185	500	430	635

Table 4. The ranking of MARCOS method and ref. methods for gear materials.

Alter.	MARCOS Method		Ref. Methods		
	$f(K_i)$	Rank	$Rank_T$	$Rank_V$	$Rank_P$
A_1	0.1878	9	9	9	9
A_2	0.3298	8	8	8	8
A_3	0.3511	6	7	6	6
A_4	0.3979	5	5	5	5
A_5	0.4673	4	4	4	4
A_6	0.7337	3	3	3	3
A_7	0.9579	1	1	1	1
A_8	0.8051	2	2	2	2
A_9	0.3448	7	6	7	7
r_s	-	-	0.98	1.00	1.00

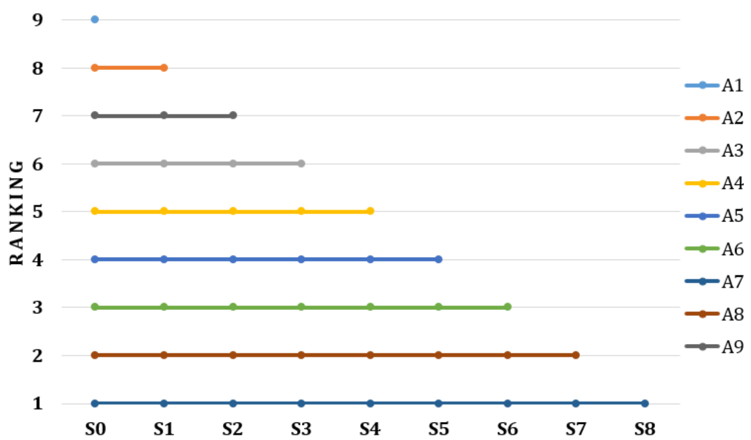

Fig. 2. The rank reversal test for material selection problem.

3.3 | Facility Layout Design Selection

The case study concerning the selection of the best facility layout design is discussed in this section. Yang et al. [31] tested the efficiency of hybrid rough set-AHP and TOPSIS method by solving the problem of selecting the best layout for a facility. They considered ten different layouts in the presence of five criteria. The criteria are space requirement (C_1), investment (C_2), transport performance (C_3), distance request (C_4) and energy saving (C_5). Among the five criteria, distance request (C_4) and energy saving (C_5) are beneficial attributes. The criteria weights are calculated using rough set-AHP method as $w_1 = 0.224$, $w_2 = 0.178$, $w_3 = 0.299$, $w_4 = 0.075$ and $w_5 = 0.224$. The data set for the layout selection problem is illustrated in *Table 5*. The PROMETHEE and AHP method were applied to the same problem as a comparison scale for TOPSIS method [31]. Hence, the three methods are compared with the ranking from MARCOS method as showed in *Table 6* where $Rank_T$, $Rank_A$ and $Rank_P$ refers to the ranking from TOPSIS, AHP and PROMETHEE respectively. The ranking reversibility in MARCOS method is checked as shown in *Fig. 3*. The method does not suffer from any rank reversals which approves the stability of MARCOS method.

Table 5. The data set for facility layout design selection problem [31].

Alter.	Criteria C_1	C_2	C_3	C_4	C_5
A_1	1012	210	259	3872	8.412
A_2	972	150	176	3530	8.358
A_3	972	270	406	3322	8.887
A_4	1217	190	208	3892	8.471
A_5	1069	195	241	3777	8.521
A_6	1069	200	234	3836	8.554
A_7	1090	220	278	3666	8.578
A_8	1139	185	199	3738	8.496
A_9	1026	230	293	3513	8.576
A_{10}	1071	165	189	3630	8.453

Table 6. The ranking of MARCOS method and ref. methods for facility layouts.

Alter.	MARCOS Method $f(K_i)$	Rank	Ref. Methods $Rank_T$	$Rank_A$	$Rank_P$
A_1	0.6518	7	7	7	6
A_2	0.7674	1	1	1	1
A_3	0.5801	10	10	9	10
A_4	0.6744	4	4	5	7
A_5	0.6631	6	6	4	5
A_6	0.6671	5	5	6	4
A_7	0.6245	8	8	10	8
A_8	0.6941	3	3	3	3
A_9	0.6202	9	9	8	9
A_{10}	0.7258	2	2	2	2
r_s	-	-	1.00	0.93	0.93

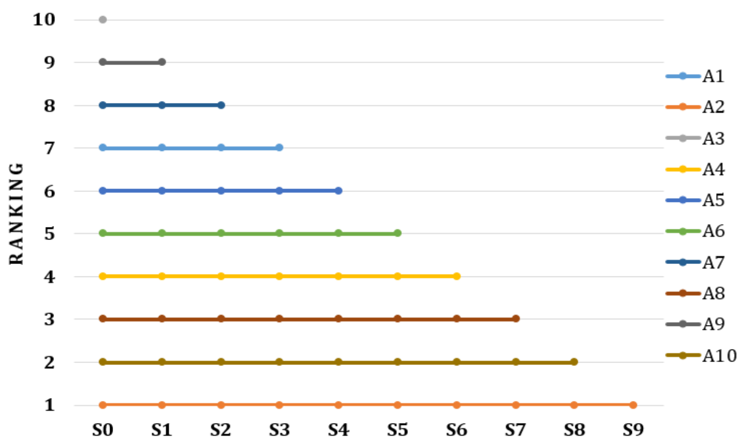

Fig. 3. The rank reversal test for material selection problem.

3.4 | Forklift Selection Problem

The selection of a side-loading forklift is discussed within this section as Fazlollahtabar et al. [32] evaluated ten forklifts to select the best forklift between them. They considered seven criteria to measure the performance of the alternative. The criteria are purchasing price (C_1), age of forklift (C_2), utilization time (C_3), maximum load capacity (C_4), maximum lift height (C_5), environmental factor (C_6) and supply of spare parts (C_7). Among the seven criteria, purchase price (C_1), age of forklift (C_2) and utilization time (C_3) are non-beneficial attributes as the lower is more preferred. The authors calculated the criteria weights using full consistency method (FUCOM) which provided the weights as $w_1 = 0.09$, $w_2 = 0.129$, $w_3 = 0.409$, $w_4 = 0.133$, $w_5 = 0.112$, $w_6 = 0.057$ and $w_7 = 0.07$. The data set for the forklift selection problem is shown in

Table 7. The WASPAS method was implemented to solve the problem and the results from WASPAS were compared to two common approaches namely, SAW and ARAS. Accordingly, the ranking from MARCOS method is compared with the ranking from the previously mentioned three MCDM methods as shown in *Table 8* where $Rank_W$, $Rank_S$ and $Rank_{AR}$ refers to the ranking from WASPAS, SAW and ARAS respectively. The rank reversal test is checked for this example as shown in *Fig. 4* which shows the stability of MARCOS method as the removal of irrelevant alternatives does not affect the ranking.

Table 7. The data set for forklift selection problem [32].

Alter.	Criteria						
	C_1	C_2	C_3	C_4	C_5	C_6	C_7
A_1	7.95	10	5012	4000	5400	5	7.67
A_2	12.9	10	7140	3000	3500	7	7.67
A_3	17.8	9	6500	5000	4500	7	5
A_4	19.3	19	4312	3000	6000	3	3.67
A_5	10.87	18	12000	3000	4000	5	3
A_6	30.4	7	4800	4000	4000	7.67	9
A_7	8.093	25	12000	4000	5900	3	5
A_8	29.8	11	3720	3000	5100	9	9
A_9	13.75	17	15350	4500	4800	3	5
A_{10}	18.297	13	6122	3000	4000	5	7

Table 8. The ranking of MARCOS method and ref. methods for forklifts.

Alter.	MARCOS Method		Ref. Methods		
	$f(K_i)$	Rank	$Rank_W$	$Rank_S$	$Rank_{AR}$
A_1	0.7184	2	2	2	2
A_2	0.5583	6	6	6	6
A_3	0.6196	5	4	5	5
A_4	0.6215	4	5	4	4
A_5	0.4153	10	10	10	10
A_6	0.7063	3	3	3	3
A_7	0.4828	8	8	8	8
A_8	0.7503	1	1	1	1
A_9	0.4329	9	9	9	9
A_{10}	0.5488	7	7	7	7
r_s	-	-	0.98	1.00	1.00

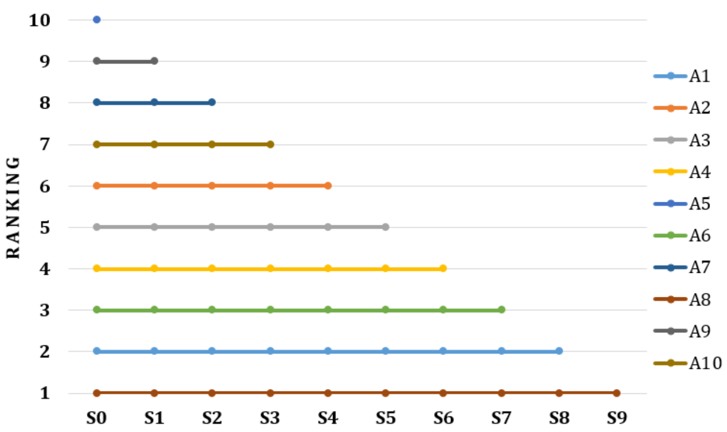

Fig. 4. The rank reversal test for forklift selection problem.

4 | Conclusions

The selection of a suitable approach to solve a decision-making problem is a complex process which consumes a lot of time from the DMs and needs to be analyzed carefully. In this study, the raw version

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of MARCOS method is used to solve four engineering problems. In each of those four problems, the number of alternatives, the number of criteria and the weighting method and are not the same. Furthermore, the MCDM methods that were implemented by past researchers to solve each problem are not of the same concept of evaluation which expanded the comparison scale for MARCOS method. The results are in favor of MARCOS method as it provided almost perfect correlation coefficients with the other MCDM methods. The rank reversal test for each problem proved that MARCOS method provides stable and consistent ranking regardless the number of alternatives being evaluated.

The MARCOS method has simple computations procedures which can be implemented easily by the DMs to any multiple criteria decision-making problem. The only limitation to MARCOS method is that it cannot handle the qualitative criteria, moreover, this limitation can be easily overcome using the fuzzy sets or grey numbers. Among the newly developed methods, the MARCOS method is the simplest and the most stable method. Thus, it is recommended to use MARCOS method for critical applications such as military, aerospace and healthcare wastes.

In this research, the applicability of MARCOS method is explored by solving four different problems that considers only quantitative data. The recommendations are to explore the applicability of the MARCOS method to deal with qualitative terms through different examples and comparisons with other MCDM methods to check the robustness of the MARCOS method. The fuzzy sets fit this type of problems as a natural extension of every MCDM method. This will approve the method is able to handle any type of multiple criteria decision-making problem under different considerations.

References

[1] Triantaphyllou, E., Shu, B., Sanchez, S. N., & Ray, T. (1998). Multi-criteria decision making: an operations research approach. *Encyclopedia of electrical and electronics engineering*, *15*(1998), 175–186.

[2] Lootsma, F. A. (1990). The French and the American school in multi-criteria decision analysis. *RAIRO-operations research*, *24*(3), 263–285.

[3] Zavadskas, E. K., & Turskis, Z. (2011). Multiple criteria decision making (MCDM) methods in economics: an overview. *Technological and economic development of economy*, *17*(2), 397–427.

[4] Voogd, H. (1982). Multicriteria evaluation with mixed qualitative and quantitative data. *Environment and planning b: planning and design*, *9*(2), 221–236.

[5] Aires, R. F. D. F., & Ferreira, L. (2018). The rank reversal problem in multi-criteria decision making: a literature review. *Pesquisa operacional*, *38*, 331–362.

[6] Saaty, T. L. (1988). What is the analytic hierarchy process? In *Mathematical models for decision support* (pp. 109–121). Springer.

[7] Hwang, C. L., & Yoon, K. (1981). Methods for multiple attribute decision making. In *Multiple attribute decision making* (pp. 58–191). Springer.

[8] Kuo, Y., Yang, T., & Huang, G. W. (2008). The use of grey relational analysis in solving multiple attribute decision-making problems. *Computers & industrial engineering*, *55*(1), 80–93.

[9] Brans, J. P., & De Smet, Y. (2016). PROMETHEE methods. In *Multiple criteria decision analysis* (pp. 187–219). Springer.

[10] Tzeng, G. H., & Huang, J. J. (2011). *Multiple attribute decision making: methods and applications*. CRC Press.

[11] Fishburn, P. C. (1967). Additive utilities with incomplete product sets: Application to priorities and assignments. *Operations research*, *15*(3), 537–542.

[12] Yazdani, M., Zarate, P., Zavadskas, E. K., & Turskis, Z. (2018). A combined compromise solution (CoCoSo) method for multi-criteria decision-making problems. *Management decision*, *57*(9), 2501-2519.

[13] Žižović, M., Pamučar, D., Albijanić, M., Chatterjee, P., & Pribićević, I. (2020). Eliminating rank reversal problem using a new multi-attribute model—The RAFSI method. *Mathematics*, *8*(6), 1015. https://doi.org/10.3390/math8061015

[14] Torkayesh, A. E., & Deveci, M. (2021). A multi-normalization multi-distance assessment (TRUST) approach for locating a battery swapping station for electric scooters. *Sustainable cities and society*, *74*, 103243. https://doi.org/10.1016/j.scs.2021.103243

[15] Pamucar, D., Žižović, M., Biswas, S., & Božanić, D. (2021). A new logarithm methodology of additive weights (LMAW) for multi-criteria decision-making: Application in logistics. *Facta universitatis, series: mechanical engineering*, 2021. https://scidar.kg.ac.rs/handle/123456789/14033

[16] Stević, Ž., Pamučar, D., Puška, A., & Chatterjee, P. (2020). Sustainable supplier selection in healthcare industries using a new MCDM method: Measurement of alternatives and ranking according to COmpromise solution (MARCOS). *Computers and industrial engineering*, *140*, 106231. DOI:10.1016/j.cie.2019.106231

[17] Chakraborty, S., Zavadskas, E. K., & Antucheviciene, J. (2015). Applications of WASPAS method as a multi-criteria decision-making tool. *Economic computation and economic cybernetics studies and research*, *49*(1), 5–22.

[18] Chakraborty, S. (2011). Applications of the MOORA method for decision making in manufacturing environment. *The international journal of advanced manufacturing technology*, *54*(9), 1155–1166.

[19] El-Araby, A., Sabry, I., & El-Assal, A. (2022). A comparative study of using mcdm methods integrated with entropy weight method for evaluating facility location problem. *Operational research in engineering sciences: theory and applications*, *5*(1), 121–138.

[20] Chakraborty, S., Chattopadhyay, R., & Chakraborty, S. (2020). An integrated D-MARCOS method for supplier selection in an iron and steel industry. *Decision making: applications in management and engineering*, *3*(2), 49–69.

[21] Badi, I., & Pamucar, D. (2020). Supplier selection for steelmaking company by using combined Grey-MARCOS methods. *Decision making: applications in management and engineering*, *3*(2), 37–48.

[22] Stević, Ž., & Brković, N. (2020). A novel integrated FUCOM-MARCOS model for evaluation of human resources in a transport company. *Logistics*, *4*(1), 4. https://doi.org/10.3390/logistics4010004

[23] Stanković, M., Stević, Ž., Das, D. K., Subotić, M., & Pamučar, D. (2020). A new fuzzy MARCOS method for road traffic risk analysis. *Mathematics*, *8*(3), 457. https://doi.org/10.3390/math8030457

[24] Torkayesh, A. E., Zolfani, S. H., Kahvand, M., & Khazaelpour, P. (2021). Landfill location selection for healthcare waste of urban areas using hybrid BWM-grey MARCOS model based on GIS. *Sustainable cities and society*, *67*, 102712. https://doi.org/10.1016/j.scs.2021.102712

[25] Miškić, S., Stević, Ž., & Tanackov, I. (2021). A novel integrated SWARA-MARCOS model for inventory classification. *International journal of industrial engineering & production research*, *32*(4), 1–17.

[26] Karaaslan, A., Adar, T., & Delice, E. K. (2022). Regional evaluation of renewable energy sources in Turkey by new integrated AHP-MARCOS methodology: a real application. *International journal of sustainable energy*, *41*(2), 103–125.

[27] Bhangale, P. P., Agrawal, V. P., & Saha, S. K. (2004). Attribute based specification, comparison and selection of a robot. *Mechanism and machine theory*, *39*(12), 1345–1366.

[28] Rao, R. V. (2007). *Decision making in the manufacturing environment: using graph theory and fuzzy multiple attribute decision making methods* (Vol. 2). Springer.

[29] Milani, A. S., Shanian, A., Madoliat, R., & Nemes, J. A. (2005). The effect of normalization norms in multiple attribute decision making models: a case study in gear material selection. *Structural and multidisciplinary optimization*, *29*(4), 312–318.

[30] Chatterjee, P., & Chakraborty, S. (2012). Material selection using preferential ranking methods. *Materials & design*, *35*, 384–393.

[31] Yang, L., Deuse, J., & Jiang, P. (2013). Multiple-attribute decision-making approach for an energy-efficient facility layout design. *The international journal of advanced manufacturing technology*, *66*(5), 795–807.

[32] Fazlollahtabar, H., Smailbašić, A., & Stević, Ž. (2019). FUCOM method in group decision-making: Selection of forklift in a warehouse. *Decision making: applications in management and engineering*, *2*(1), 49–65.

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Classifications of Linking Activities Based on Their Inefficiencies in Network DEA

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Abstract

Network DEA models deal with measurements of relative efficiency of Decision-Making Units (DMUs) when the insight of their internal structures is available. In network models, sub-processes are connected by links or intermediate products. Links have the dual role of output from one division or sub-process and input to another one. Therefore, improving the efficiency score of one division by increasing its output may reduce the score of another division because of increasing its input. To address this conflict, in the present paper we proposed a new approach in Slack-Based Measure (SBM) framework which provides deeper insights regarding the sources of inefficiency. The proposed approach is a two-phase procedure in which Phase-I determine the role of intermediate measures by solving a linear program and partitions the intermediate measures into three groups of "input type", "output type" and "fixed-flows" and Phase-II measures the scores of the DMUs under evaluation. Providing a classification for intermediate products and account their excesses or shortfalls in efficiency calculation while the continuity of link flows between subunits are kept, are the advantages of the proposed approach.

Keywords: Network DEA, Intermediate product, SBM, Efficiency score.

1 | Introduction

Data Envelopment Analysis (DEA) was developed to measure the relative efficiency of operational units called "Decision Making Units (DMUs)" [1] that consume multiple inputs to produce multiple outputs. In its original settings, the operations and interrelations of the processes within the DMU are neglected and only the inputs to the DMU and outputs from it are considered. In the literature of DEA this approach is called black box and the associated model is called black box model.

In real world problems organizations have complex internal structures and many of them consist of several divisions or sub-units/processes that are linked together by products or services.

Regarding efficiency evaluation of multi-division organizations, in many situations, analysts considered the subunits as independent DMUs, and calculated their efficiencies separately. This approach is thus

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called separation approach and the associated model as separation model. In separation approach the links between two sub-units have the both role of input to one sub-unit and output from another one, hence the complex structure can be divided into sub-units or divisions and for each division some benchmarks can be found. Since links are treated as discretionary inputs or outputs, the separation model takes into account the inefficiency associated with the linking activities but does not keep the continuity of flows between subunits.

In the literature of DEA many researchers are interested in investigating the sources of inefficiency within the DMUs with complex structure and measuring divisional efficiencies as well as the overall efficiency in a unified framework. To accomplish this, researchers have developed Network DEA methodologies which are more sensitive in detecting inefficiencies than traditional DEA models.

Network DEA models were introduced for the first time to the literature of DEA by Färe and Grosskopf [2], [3]. After pioneering work of Färe and Grosskopf [2], a significant number of researchers and scholars have abandoned the black box perspective and started to look into the black box.

A network structure can be a simple two-stage process or a complex system with multiple divisions that are linked together with intermediate measures. Linking activities or intermediate measures are indispensable parts of Network DEA models. Since they play the both roles of input to one division and output from another one, their existence is the major problem in measuring overall and divisional efficiencies of a network. Improving the efficiency of one division by increasing its outputs may reduce the efficiency of another division due to the increased amount of inputs. Similarly, raising efficiency score of one division by reducing the amount of its input may reduce the efficiency of the other division due to producing output. Since standard DEA models do not resolve this conflict, they are not a good choice for assessing the efficiency of DMUs with network structure and therefore, many scholars and researchers have proposed their own solutions.

For instance, Yong et al. [4] defined the overall efficiency score as a product of stages' efficiency scores. They applied the input-oriented VRS model to measure the efficiency of the first stage and the output-oriented VRS model to measure the efficiency of the second stage.

Kao and Hwang [5] also defined the overall efficiency score of the two-stage structure as the geometric mean of stage efficiencies. Liang et al. [6] also use such multiplicative efficiency decomposition in their study. They use the concepts of the Stackelberg game (or leader-follower) and the centralized or cooperative game to evaluate the overall efficiency score.

Lewis and Sexton [7] proposed a Network DEA model with two-stage structure for measuring the efficiency of Major League Baseball (MLB) teams. Their methodology provides efficiency scores for each stage and overall efficiency. In 2004, they extended their model to a multi stage structure and in 2013 they propose an un-oriented two-stage DEA methodology to measure efficiency of MLB teams during the 2009 season [8], [9].

All Network DEA models mentioned above apply the CCR [1] or the BCC [10] models as the basic DEA methodology and the production possibility set. In other words, they apply the radial measure of efficiency that rely on the assumption that DMU's efficiency score depends on its proportional distance to the efficiency frontier. However, in real words problems some inputs and outputs are substitutional and do not change proportionally. Non-radial models have the advantage of measuring efficiencies in the case that inputs and outputs change non-proportionally. One of the most popular non-radial models in the literature of DEA is Slack-Based Measure (SBM) model [11], [12]. Non-radial SBM models deal with slacks directly and do not consider the assumption of changing inputs and outputs proportionally.

Tone and Tsutsui [13] develop a slacks-based Network DEA model by using the production possibility Sets. In their study intermediate measures are called links. They considered the component efficiency as

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a function of slack variables and the overall efficiency as a weighted average of the component efficiencies. In their study the component weights are determined exogenously to represent the importance of the components. They proposed two possible cases for linking activities, called fixed link and free link. In both cases the continuity of link flows between components is kept. Fukuyama and Weber [14] proposed a measure for efficiency called network directional SBM. They normalized values of the slack variables by user defined coefficients.

Paradi et al. [15] proposed a modified Slacks-Based Measure (SBM) for evaluating efficiency of a DMU with two-stage structure to aggregate the obtained efficiency scores from the stages and generate a composite performance index for each unit.

Lozano [16] proposed an SBM model for measuring efficiency of networks. In their proposed approach the target inputs, outputs and intermediate products of each process may be larger or smaller than their observed values. By relaxing the constraints for both the fixed-link and the free-link cases they improved the discriminating power of their model.

Shamsijamkhaneh et al. [17] proposed an approach which categorizes the intermediate measures into either input or output type endogenously, and keeps the continuity of link flows between divisions. Based on their approach they proposed two models to study on direct and indirect effect of inefficiency arising from intermediate measure in efficiency measurement.

In this paper we propose a two-phase procedure in SBM framework to measure the overall and divisional efficiencies of the DMUs under consideration. The proposed procedure accounts the excesses or shortfalls of intermediate measures into the objective function. The major contribution of this paper is to address the conflict caused by the dual role of intermediate measures and incorporate their excesses and shortfalls in efficiency measurement. The main novelty in our proposed approach lies in the more flexible manner in which we categorize the intermediate measures by allowing them to have a small violation from their observed values and ignoring their small excesses and shortfalls.

Kord et al. [18] proposed a new Network DEA model to evaluate the sustainability of agricultural performance in the cities of Sistan-Baluchestan Province of Iran in the presence of stochastic data. They considered two stages for agricultural practices: the environmental stage (planting and maintaining) and the economic stage (harvesting), which use shared resources.

Abdali et al. [19] proposed a multiplier two-stage network that simulate the internal structure of network systems in parallel-series structure in the presence of non-discretionary inputs and shared discretionary inputs between sub-DMUs.

Pereira et al. [20] proposed a Network DEA model to measure the performance of countries in struggle against health crises like SARS-CoV-2. They considered the countries as dmus with a general series structure with five stages, population, contagion, triage, hospitalization, and intensive care unit admission. They suggested an output orientation model for a social perspective, and an input orientation model for a financial perspective.

Hamzah et al. [21] and Mariano et al. [22] evaluated the performance of heath system in Brazil and Malaysia, respectively in fighting against COVID-19.

Zhang et al. [23] stated all models in Network DEA literature generally assume radial or non-radial point of views to declare internal structures of DMUs and no study used the intermediate point of view to construct a Network DEA model. To fill the literature gap, they proposed a model which combines the intermediate approach with Network DEA and develop a new approach to measure the efficiency of a network.

Roudabr et al. [24] proposed a novel model on the basis of Network DEA to determine the most suitable benchmarks for DMUs and SUB-DMUs. In their proposed model, input and output values consider to have nonlinear values. They applied their proposed model to determine the benchmark for cement factories listed on the Tehran Stock Exchange.

Zhu et al. [25] introduced a model based on Mixed Integer Linear Program (MILP) which finds the most efficient targets on the extended production possibility set in DEA.

Yang et al. [26] applied Network DEA on water systems by proposing a dynamic interactive network SBM model. They considered the water systems as two water subsystems, Water Use Subsystem (WUS) and a Wastewater Treatment Subsystem (WTS) and evaluated the relative efficiency of regional industrial water systems in China.

Li et al. [27] applied a four-stage Network DEA based on SBM to measure the total factor waste gas treatment efficiency in steel and iron industries in China. They entered the data of 65 Chinese company during the years 2005-2014 in their model.

The rest of this paper is structured as follows; Section 2 presents some preliminaries and notation. Section 3 presents our proposed procedure to address the issue regarding the dual role of intermediate measures. To verify our proposed procedure, we provide a numerical example in Section 4 and compare the procedure with some existing approaches in Network DEA. Finally, Section 5 concludes the paper.

2 | Preliminaries

In this section, we will review some fundamental backgrounds required in this paper.

Suppose that there are a set of n DMUs indexed by consisting of K divisions that Division K (Divk) consumes inputs and produces outputs. Let and, respectively, be input vector to and output vector from Divk. Intermediate products from Divk to Divh are also denoted by where is the number of intermediate measures from Divk to Divh and denotes the set of links.

Tone and Tsutsui [13] propose a Network DEA (NDEA) model based on the Weighted Slacks-Based Measure (WSBM) approach to measure the overall and divisional efficiencies of the network. Their model presented as follows:

$$\rho = \min \sum_{k=1}^{K} w_k \left[\frac{1-\frac{1}{m_k}\left(\sum_{i=1}^{m_k}\frac{s_{pi}^{k-}}{x_{ip}}\right)}{1+\frac{1}{r_k}\left(\sum_{r=1}^{r_k}\frac{s_{rp}^{k+}}{y_{rp}}\right)} \right], \tag{1}$$

$$\text{s.t.} \quad \sum_{j=1}^{n} \lambda_j^k x_{ij}^k + s_{ip}^{k-} = x_{ip}^k, \quad (k=1,\dots,K),(i=1,\dots,m_k), \tag{2}$$

$$\sum_{j=1}^{n} \lambda_j^k y_{rj}^k - s_{rp}^{k+} = y_{rp}^k, \quad (k=1,\dots,K),(r=1,\dots,r_k), \tag{3}$$

$$\textstyle\sum_{j=1}^{n} \lambda_j^k z_{dj}^{(k,h)} = z_{dp}^{(k,h)} \quad (\text{for all } (k,h)),(d=1,\dots,l_{(k,h)}), \tag{4}$$

$$\textstyle\sum_{j=1}^{n} \lambda_j^h z_{dj}^{(k,h)} = z_{dp}^{(k,h)} \quad (\text{for all } (k,h)),(d=1,\dots,l_{(k,h)}), \tag{5}$$

$$\textstyle\sum_{j=1}^{n} \lambda_j^k = 1 \quad (\text{for all } k), \tag{6}$$

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$$\lambda_j^k \geq 0 \quad \text{for all} j,k), s_{rp}^{k+} \geq 0 \quad \text{for all } r,k), s_{ip}^{k-} \geq 0 \quad \text{for all } r,k), s_{dp}^{k,h)-} \geq 0 \ \text{(for all } d, \text{ for all } (k,h)), s_{dp}^{k,h)+} \geq 0 \ \text{(for all } d, \ \text{for all } (k,h)), \tag{7}$$

where is the intensity weight corresponding to Divk of DMUj, and is also the relative weight of Divk which is determined exogenously by decision maker to represent its importance and $\sum_{k=1}^{K} w^k = 1$, $w^k \geq 0 \ (for \ all \ k)$.

It should be noted that the model presented above computes the non-oriented overall efficiency of DMUp under the assumption of Variable Returns-to-Scale (VRS) for production. Removing *Constraint (6)* changes the assumption of VRS to the Constant Returns-to-Scale (CRS) for production. Tone and Tsutsui [13] proposed the input and output-oriented case of their model by minimizing the numerator and maximizing the denominator of the objective *Function (1)*, respectively.

In the model presented above, linking *Constraints (4)* and *Constraint (5)* are kept unchanged and fixed, and the intermediate products are beyond the control of DMUs. Tone and Tsutsui [13] called this case as "fixed" link value case.

Substituting *Constraint (4)* and *Constraint (5)* by *Constraint (8)*, they introduced another possible case for linking activities called "free" link value case in which the linking activities can be freely determined.

$$\sum_{j=1}^{n} \lambda_j^k z_{dj}^{(k,h)} = \sum_{j=1}^{n} \lambda_j^h z_{dj}^{(k,h)} \quad \text{for all } (k,h)(d = 1,\ldots,l_{(k,h)}). \tag{8}$$

Note that in both cases the continuity of link flows between divisions are kept.

In the case that intermediate measures are categorized into either input type or output type exogenously by decision maker, Tone and Tsutsui [13] incorporate the input excesses and output shortfalls by setting the linking *Constraint (9)* and *Constraint (10)* and modifying the objective *Functions (1)* to *(11)*.

As output to Divh

$$\begin{aligned} &\sum_{j=1}^{n} \lambda_j^k z_j^{(k,h)} - s_{dp}^{(k,h)+} = z_{dp}^{(k,h)}, \\ &\sum_{j=1}^{n} \lambda_j^h z_{dj}^{(k,h)} = \sum_{j=1}^{n} \lambda_j^k z_{dj}^{(k,h)}. \end{aligned} \tag{9}$$

As input to Divh

$$\begin{aligned} &\sum_{j=1}^{n} \lambda_j^h z_j^{(k,h)} + s_o^{(k,h)-} = z_o^{(k,h)}, \\ &\sum_{j=1}^{n} \lambda_j^k z_{dj}^{(k,h)} = \sum_{j=1}^{n} \lambda_j^k z_{dj}^{(k,h)}. \end{aligned} \tag{10}$$

$$\eta_p^* = \min \sum_{k=1}^{K} w_k \left[\frac{1 - \frac{1}{m_k + l_k} \left(\sum_{i=1}^{m_k} \frac{s_{pi}^{k-}}{x_{ip}} + \sum_{h \in F_k}^{h_k} \frac{s_{hp}^{(h,k)-}}{z_{hp}^{(k,f)}} \right)}{1 + \frac{1}{r_k + t_k} \left(\sum_{r=1}^{r_k} \frac{s_{rp}^{k+}}{y_{rp}} + \sum_{t=1}^{t_k} \frac{s_{tp}^{(k,f)+}}{z_{tp}^{(k,f)}} \right)} \right], \tag{11}$$

where $\sum_{k=1}^{K} w_k = 1,\ w_k \geq 0\ \ (for\ all\ k)$. t_k is the number of those intermediate products that are considered as output from Divk and l_k is the number of those intermediate products that are considered as input to Divk.

There are many situations in which the intermediate measures cannot be categorized into input or output type by the decision maker. For instance, consider the buyer-seller supply chain presented in Liang et al. [28] the supplier's revenue is an output from the seller, and seller wants to increase it while also an input to the buyer and buyer interested to decrease it. Therefore, there is always a conflict between buyer and seller and minimizing the total supply chain cost or maximizing the total supply chain revenue (profit).

In the next section we propose a two-phase procedure in SBM framework which classifies the intermediate measures into three groups of "input type", "output type" and "fixed-flows" and identifies the potential improvements regarding linking activities.

3 | Proposed Procedure

In this section we introduce a Two-Phase procedure to measure the relative efficiencies of DMUs with network structure. This procedure addresses the issue regarding dual role of intermediate measures in efficiency measurement and incorporate inefficiencies associated with intermediate measures in efficiency measurement. Phase-I is a linear program model which partitions intermediate measures into three groups of "input type", "output type" and "fixed-flows". According to the results obtained from Phase-I, in Phase-II we use SBM model to determine the slack of each input, output and intermediate measure and we incorporate these slacks in measuring efficiencies of the DMUs under consideration.

Phase-I

As we discussed earlier, in Phase-I we propose a linear program to partition the intermediate products into input type, output type and fixed- flows. We use the linear program in *Eqs. (12)* to *(18)* for Phase-I.

$$\beta = \max \sum_{k=1}^{K} w_k \left(\sum_{i=1}^{m_k} \frac{s_{pi}^{k-}}{x_{ip}} + \sum_{r=1}^{r_k} \frac{s_{rp}^{k+}}{y_{rp}} + \sum_{d=1}^{l_{(k,h)}} \frac{s_{dp}^{(k,h)+}}{z_{dp}} + \sum_{d=1}^{l_{(k,h)}} \frac{s_{dp}^{(k,h)-}}{z_{dp}} \right). \tag{12}$$

$$\text{s.t.} \quad \sum_{j=1}^{n} \lambda_j^k x_{ij}^k = x_{ip}^k - s_{ip}^{k-}, \quad (k=1,\dots,K),(i=1,\dots,m_k), \tag{13}$$

$$\sum_{j=1}^{n} \lambda_j^k y_{rj}^k = y_{rp}^k + s_{rp}^{k+}, \quad (k=1,\dots,K),(r=1,\dots,r_k), \tag{14}$$

$$\sum_{j=1}^{n} \lambda_j^k z_{dj}^{(k,h)} = z_{dp}^{(k,h)} - s_{dp}^{(k,h)-} + s_{dp}^{(k,h)+} \quad (\text{for all } (k,h)),(d=1,\dots,l_{(k,h)}), \tag{15}$$

$$\sum_{j=1}^{n} (\lambda_j^h - \lambda_j^k) z_{dj}^{(k,h)} = 0 \quad (\text{for all } (k,h)),(d=1,\dots,l_{(k,h)}), \tag{16}$$

$$\sum_{j=1}^{n} \lambda_j^k = 1 \quad (\text{for all } k), \tag{17}$$

$$\begin{aligned} &\lambda_j^k \geq 0\ (\text{for all } j,k), s_{rp}^{k+} \geq 0 \quad (\text{for all } r,k),\ s_{ip}^{k-} \geq 0 \quad (\text{for all } r,k), s_{dp}^{(k,h)-} \geq 0 \\ &(\text{for all } d, \text{for all } (k,h)),\ s_{dp}^{(k,h)+} \geq 0 \quad (\text{for all } d,\ \text{for all } (k,h)). \end{aligned} \tag{18}$$

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In Phase-I, the objective function maximizes the total improvement ratios of each input, output and intermediate measure of DMU_p. The set of left-side of *Constraint (13)* to *Constraint (17)* is the efficient frontier with respect to DMU_p. The right-side of *Eq. (13)* is the improved ith input at Divk located on the frontier.

The right-side of *Constraint (14)* is the expanded rth output at Divk located on the frontier.

The right-side of *Constraint (15)* is the improved dth link between Divk and Divh located on the frontier.

It should be noted the slack vectors related to $s_{dp}^{(k,h)-}$ and $s_{dp}^{(k,h)+}$ could not have been used to form a basis simultaneously, since they are linearly dependent; hence at least one of these variables is nonbasic and its optimal value is zero.

In particular, the following conditions must hold at optimality:

I. $s_{dp}^{(k,h)-}$ is basic and $s_{dp}^{(k,h)+}$ is nonbasic ($s_{dp}^{(k,h)+}=0$). In this case the corresponding intermediate measure is considered as input to Divh. Let $D^{(k,h)-}$ denote the set of links that are considered as output from Divk.

II. $s_{dp}^{(k,h)+}$ is basic and $s_{dp}^{(k,h)-}$ is nonbasic ($s_{dp}^{(k,h)-}=0$). In this case the corresponding intermediate measure is considered as output from *Divk* and we denote the set of these links by $D^{(k,h)+}$.

III. $s_{dp}^{*(k,h)+}$ and $s_{dp}^{*(k,h)-}$ are both nonbasic ($s_{dp}^{*(k,h)-}=s_{dp}^{*(k,h)+}=0$). In this case the corresponding link is fixed and kept unchanged. We denote the set of these intermediate measures by $D_{fixed}^{(k,h)}$.

Refer to explanations above it is easy to conclude that $D^{(k,h)-}\cup D^{(k,h)+}\cup D_{fixed}^{(k,h)}=D^{(k,h)}$ and $D^{(k,h)-}\cap D^{(k,h)+}\cap D_{fixed}^{(k,h)}=\varphi$.

Phase-II

According to the results obtained from Phase-I, in Phase-II we aim to measure the relative efficiencies of DMUs by incorporating the inefficiency associated with intermediate measures in efficiency measurement. We use the linear program *Eqs. (19)* to *(27)* for Phase-II that is the input-oriented SBM under VRS assumption for evaluating efficiency score. The non-oriented or output-oriented models can also be utilized for Phase-II.

$$\varphi_p^* = \min \sum_{k=1}^{K} w_k \left[1 - \frac{1}{m_k + \left|D^{(f,k)-}\right|} \left(\sum_{i=1}^{m_k} \frac{s_{ip}^{k-}}{x_{ip}} + \sum_{d=1}^{\left|D^{(f,k)-}\right|} \frac{s_{dp}^{(f,k)-}}{z_{dp}^{(f,k)}} \right) \right], \tag{19}$$

$$\text{s.t.} \quad \sum_{j=1}^{n} \lambda_j^k x_{ij}^k = x_{ip}^k - s_{ip}^{k-}, \quad (k=1,\dots,K),(i=1,\dots,m_k), \tag{20}$$

$$\sum_{j=1}^{n} \lambda_j^k y_{rj}^k = y_{rp}^k + s_{rp}^{k+}, \quad (k=1,\dots,K),(r=1,\dots,r_k), \tag{21}$$

$$\sum_{j=1}^{n} \lambda_j^h z_{dj}^{(k,h)} = z_{dp}^{(k,h)} - s_{dp}^{(k,h)-} \quad \text{for all } (k,h), d\in D^{(k,h)-}, \tag{22}$$

$$\sum_{j=1}^{n} \lambda_j^k z_{dj}^{(k,h)} = z_{dp}^{(k,h)} + s_{dp}^{(k,h)+} \quad \text{for all } (k,h), d\in D^{(k,h)+}, \tag{23}$$

$$\sum_{j=1}^{n} \lambda_j^k z_{dj}^{(k,h)} = z_{dp}^{(k,h)} \quad \text{for all } (k,h), d \in D_{\text{fixed}}^{(k,h)}, \tag{24}$$

$$\sum_{j=1}^{n} (\lambda_j^h - \lambda_j^k) z_{dj}^{(k,h)} = 0 \quad (\text{for all } (k,h)), (d = 1, \ldots, l_{(k,h)}), \tag{25}$$

$$\sum_{j=1}^{n} \lambda_j^k = 1 \quad (\text{for all } k), \tag{26}$$

$$\begin{gathered}\lambda_j^k \geq 0 \quad (\text{for all } j,k),\ s_{rp}^{k+} \geq 0 \quad (\text{for all } r,k),\ s_{ip}^{k-} \geq 0 \quad (\text{for all } r,k), s_{dp}^{(k,h)-} \geq 0 \\ (\text{for all } d,\ \text{for all } (k,h)),\ s_{dp}^{(k,h)+} \geq 0 \quad (\text{for all } d,\ \text{for all } (k,h)).\end{gathered} \tag{27}$$

The objective *Function (19)* states the minimum mean proportional reduction rate of inputs or input mix inefficiencies.

Theorem 1. For the proposed procedure, every division has at least one divisionally efficient DMU.

Proof: As we noticed earlier in Phase-I the intermediate measures are partitioned into input type, output type and fixed- flows. Therefore, the proposed procedure in Phase-II can be reduced to the Separation model with non-discretionary inputs and outputs corresponding to the fixed-flows. Hence, we can solve this case separately division by division. Therefore, every division has at least one efficient DMU in the division.

4 | Numerical Example

In this section to verify our proposed procedure, we present a numerical example and compare the results with NSBM model in free-link case.

Consider the numerical example given in *Table 1* where we have seven DMUs consist of 3 divisions and each division has a single exogenous input. There are two final outputs which correspond to Div2 and Div3 and there are two intermediate products that one links Div1 to Div2 and the other links Div2 to Div3. *Fig. 1* displays the network structure of the DMUs under consideration.

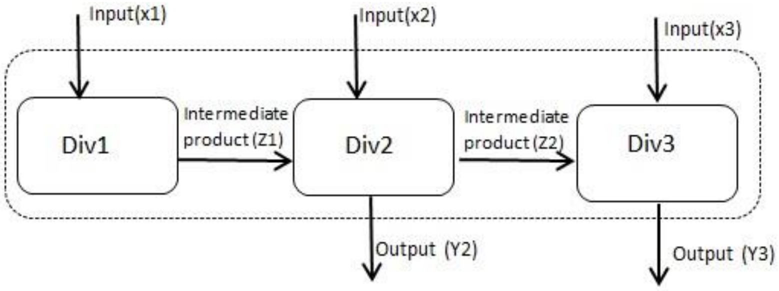

Fig. 1. Network structure of the DMUs.

Table 1. Data for numerical example.

DMU	Div1 Input1 (x_1)	Div2 Input2 (x_2)	Output2 (y_2)	Div3 Input3 (x_3)	Output3 (y_3)	link Link12 (z_1)	Link23 (z_2)
DMU1	1.5	1.2	1.5	2.5	1.1	1	1.5
DMU2	1.25	1.5	2	1.1	2.5	0.4	0.8
DMU3	1.45	0.75	1.1	3	3	2.8	2
DMU4	1.25	1	1	1.2	1	4.5	4
DMU5	1.3	0.25	1.2	1.9	0.8	2.9	2.2
DMU6	2	1	1.25	1.2	2.2	2.1	2.5
DMU7	1.1	0.75	1.4	1.8	1.9	1.5	0.9

In this section we consider the numbers 0.4, 0.2 and 0.4 as the weights to Div1, Div2 and Div3, respectively in models and we utilize input-oriented SBM under the VRS assumption for efficiency evaluation in all models.

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4.1 | The Results Obtained by Proposed Procedure

In this subsection we use the proposed procedure to obtain the overall and divisional scores of the DMUs with data exhibited in *Table 1*.

As we discussed earlier, Phase-I partitions the intermediate measures into three groups of input type, output type and fixed flows. *Table 2* represents the results of Phase-I.

Table 2. The results obtained by solving Phase-I.

DMU	Obj	s^{*1-}	s^{*2-}	s^{*3-}	s^{*2+}	s^{*3+}	$s^{*(1,2)+}$	$s^{*(1,2)-}$	Type of z1	$s^{*(2,3)-}$	$s^{*(2,3)+}$	Type of z2
DMU1	2.104	1.222	0.109	1.218	0.173	0.182	0	0	Input	0	0.645	Fixed
DMU2	0.911	1.139	0	0	0	0	0	0	Fixed	0	0	Fixed
DMU3	0.778	0.831	0	0	0	0	0	0.572	Input	0	0	Fixed
DMU4	3.167	0.444	0.750	0.144	0.2	0.936	0	1.6	Input	1.8	0	Input
DMU5	2.245	0.494	0	0.844	0	1.136	0	0	Fixed	0	0	Fixed
DMU6	1.767	1.632	0	0.065	0	0.194	0	0.775	Input	1.1	0	Input
DMU7	1.246	0	0	0	0	0	0.4	0	Output	0	0.882	Output

Intermediate measure Z1 is considered as input to Div2 in DMU3, DMU4 and DMU6 and intermediate measure Z2 is considered as input to Div3 in DMU1, DMU4 and DMU6. Intermediate measure Z1 is kept unchanged in DMU1, DMU2 and DMU5 and intermediate measure Z2 is kept unchanged in DMU2, DMU3 and DMU5. Both Z1 and Z2 are considered as outputs from Div1 and Div2, respectively, in DMU7.

With the partitions of the links exhibited in *Table 2*, we are ready to employ Phase-II. Divisional and overall scores for the DMUs are listed in *Table 3*.

Table 3. Divisional and overall scores of the DMUs obtained from proposed procedure.

DMU	Overall	Div1	Div2	Div3
DMU1	0.302	0.185	0.794	0.173
DMU2	0.636	0.089	1.000	1.000
DMU3	0.601	0.353	0.229	1.000
DMU4	0.192	0.044	0.397	0.238
DMU5	0.602	0.620	1.000	0.385
DMU6	0.355	0.057	0.575	0.544
DMU7	0.694	0.379	1.000	0.485

4.2 | Comparisons of Scores between Proposed Procedure and NSBM

In this subsection we compare our proposed approach with NSBM in free link case proposed by Tone and Tsutsui [13]. *Table 6* exhibits the results obtained by NSBM model in free-link case.

Table 4. The results of NSBM model in free-link case.

	Overall Efficiency	Divisional Efficiency			Initial Input Slacks		
DMU	Free-link	Div1(0.4)	Div2(0.2)	Div3(0.4)	s^{*1-}	s^{*2-}	s^{*3-}
DMU1	0.332	0.156	0.938	0.206	1.417	0.075	1.984
DMU2	0.636	0.089	1.000	1.000	1.139	0.000	0.000
DMU3	0.665	0.504	0.314	1.000	0.719	0.515	0.000
DMU4	0.318	0.044	0.750	0.375	1.194	0.250	0.750
DMU5	0.602	0.620	1.000	0.385	0.494	0.000	1.169
DMU6	0.526	0.079	0.860	0.807	1.886	0.046	0.232
DMU7	0.694	0.379	1.000	0.485	0.683	0.000	0.926

Fig. 2 illustrates the comparison of the results obtained by proposed procedure and NSBM model in free-link case. It can bee seen that how the inefficiencies associated with linking activities exert influence over

divisional and overall efficiency of each DMU. Considering the feasible regions of the proposed procedure and NSBM free-link case, it can be easily concluded that the feasible region of NSBM free link case contains the feasible region of Phase-II.

The objective of phase-II can take values smaller than or equal to those of NSBM model, hence it can be certainly said that the scores obtained by the proposed approach are not definitely higher than those of NSBM.

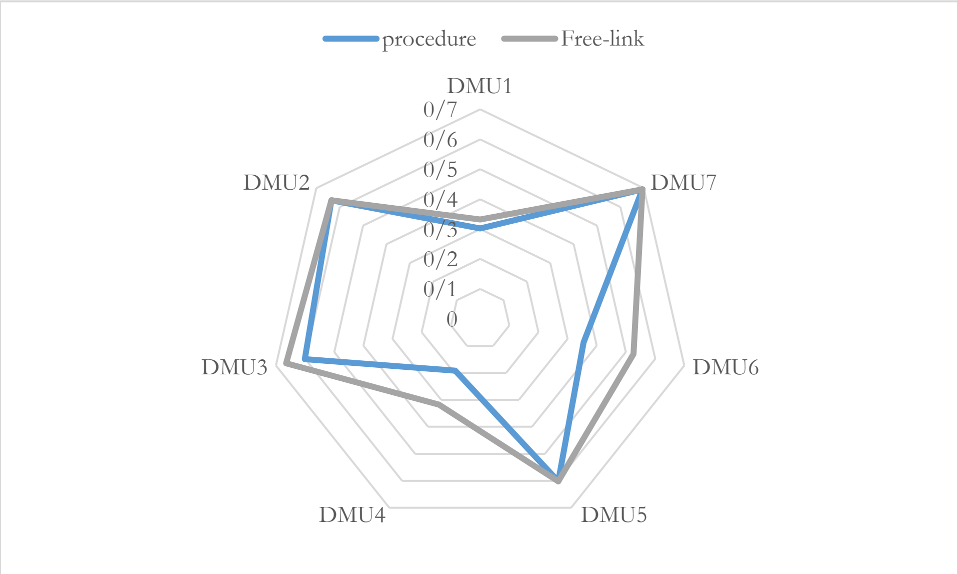

Fig. 2. Comparisons of overall efficiency scores.

Comparing the results obtained by proposed procedure and free-link case shows that DMU2, DMU5 and DMU7 have the same efficiency score in both models. This means that intermediate measures in these dmus do not have any excesses. Comparing the scores obtained by both models for DMU4 shows that there are significant inefficiencies due to intermediate measures which are considered as inputs to divisions 2 and 3 by the model and both model evaluated the lowest efficiency score for DMU4. According to both models DMU7 have the highest score among the other DMUs. The different scores for DMU1 indicates the inefficiency due to intermediate measure which is detected by the model as input to division2.

5 | Conclusion

To address the potential conflict caused by the dual role of intermediate measures and incorporate the inefficiencies associated with intermediate measures in efficiency measurement in this paper we proposed a new procedure in SBM frame work. The proposed approach has the advantage of optimizing the system structure and the slack values simultaneously and partitions the intermediate measures. Phase-I determines the role of intermediate measures by solving a linear programming and partitions the intermediate measures into three groups of input type, output type and fixed flows. The objective of Phase-I maximizes the total improvement ratios of each input, output and intermediate measures of the DMU under consideration. With the partitions of the links in Phase-I, we employ Phase-II to measure the scores of the DMUs under consideration. We demonstrated that for the proposed procedure in Phase-II, every division has at least one divisionally efficient DMU. For further research we can suggest the following issues.

Extending the procedure to the situation in which some input/output data are fuzzy numbers. Another possible line of research is to extend the procedure to the dynamic network models.

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References

[1] Charnes, A., Cooper, W. W., & Rhodes, E. (1978). Measuring the efficiency of decision making units. *European journal of operational research*, *2*(6), 429–444.

[2] Färe, R. (1991). Measuring Farrell efficiency for a firm with intermediate inputs. *Academia economic papers*, *19*(2), 329–340.

[3] Färe, R., Grosskopf, S. (2000). Network DEA. *Socio-economic planning sciences*, *34*(1), 35–49.

[4] Yong, Z. H. A., Liang, L., & Xu, C. (2008). Two-stage BCC model for cooperative efficiency evaluation using a geometric mean method. *Systems engineering-theory & practice*, *28*(10), 53–58.

[5] Kao, C., & Hwang, S. N. (2008). Efficiency decomposition in two-stage data envelopment analysis: An application to non-life insurance companies in Taiwan. *European journal of operational research*, *185*(1), 418–429.

[6] Liang, L., Cook, W. D., & Zhu, J. (2008). DEA models for two-stage processes: Game approach and efficiency decomposition. *Naval research logistics (NRL)*, *55*(7), 643–653.

[7] Sexton, T. R., & Lewis, H. F. (2003). Two-stage DEA: An application to major league baseball. *Journal of productivity analysis*, *19*, 227–249.

[8] Lewis, H. F., & Sexton, T. R. (2004). Network DEA: efficiency analysis of organizations with complex internal structure. *Computers & operations research*, *31*(9), 1365–1410.

[9] Lewis, H. F., Mallikarjun, S., & Sexton, T. R. (2013). Unoriented two-stage DEA: The case of the oscillating intermediate products. *European journal of operational research*, *229*(2), 529–539.

[10] Banker, R. D., Charnes, A., & Cooper, W. W. (1984). Some models for estimating technical and scale inefficiencies in data envelopment analysis. *Management science*, *30*(9), 1078–1092.

[11] Tone, K. (2001). A slacks-based measure of efficiency in data envelopment analysis. *European journal of operational research*, *130*(3), 498–509.

[12] Pastor, J. T., Ruiz, J. L., & Sirvent, I. (1999). An enhanced DEA Russell graph efficiency measure. *European journal of operational research*, *115*(3), 596–607.

[13] Tone, K., & Tsutsui, M. (2009). Network DEA: A slacks-based measure approach. *European journal of operational research*, *197*(1), 243–252.

[14] Fukuyama, H., & Weber, W. L. (2010). A slacks-based inefficiency measure for a two-stage system with bad outputs. *Omega*, *38*(5), 398–409.

[15] Paradi, J. C., Rouatt, S., & Zhu, H. (2011). Two-stage evaluation of bank branch efficiency using data envelopment analysis. *Omega*, *39*(1), 99–109.

[16] Lozano, S. (2015). Alternative SBM model for network DEA. *Computers & industrial engineering*, *82*, 33–40.

[17] Shamsijamkhaneh, A., Hadjimolana, S. M., Rahmani Parchicolaie, B., & Hosseinzadehlotfi, F. (2018). Incorporation of inefficiency associated with link flows in efficiency measurement in network DEA. *Mathematical problems in engineering*, *2018*, 1–12.

[18] Kord, A., Payan, A., & Saati, S. (2022). Network DEA Models with stochastic data to assess the sustainability performance of agricultural practices: an application for Sistan and Baluchestan Province in Iran. *Journal of mathematics*, *2022*, 1–19.

[19] Abdali, E., Moradipour, K., Asadi-Rahmati, S., & Fallah, M. (2022). Efficiency evaluation in hybrid two-stage network DEA with non-discretionary inputs and shared discretionary inputs. *International journal of computer mathematics: computer systems theory*, *7*(1), 33–41.

[20] Pereira, M. A., Dinis, D. C., Ferreira, D. C., Figueira, J. R., & Marques, R. C. (2022). A network data envelopment analysis to estimate nations' efficiency in the fight against SARS-CoV-2. *Expert systems with applications*, *210*, 118362. https://www.sciencedirect.com/science/article/pii/S0957417422014774

[21] Md Hamzah, N., Yu, M. M., & See, K. F. (2021). Assessing the efficiency of Malaysia health system in COVID-19 prevention and treatment response. *Health care management science*, *24*, 273–285.

[22] Mariano, E., Torres, B., Almeida, M., Ferraz, D., Rebelatto, D., & de Mello, J. C. S. (2021). Brazilian states in the context of COVID-19 pandemic: an index proposition using Network Data Envelopment Analysis. *IEEE latin america transactions*, *19*(6), 917–924.

[23] Zhang, R., Wei, Q., Li, A., & Chen, S. (2022). A new intermediate network data envelopment analysis model for evaluating China's sustainability. *Journal of cleaner production*, *356*, 131845. https://www.sciencedirect.com/science/article/pii/S095965262201455X

[24] Roudabr, N., Najafi, S. E., Moghaddas, Z., Movahedi Sobhani, F., & others. (2022). Overall efficiency of four-stage structure with undesirable outputs: a new SBM network DEA model. *Complexity*, *2022*. https://www.hindawi.com/journals/complexity/2022/9577175/

[25] Zhu, Q., Aparicio, J., Li, F., Wu, J., & Kou, G. (2022). Determining closest targets on the extended facet production possibility set in data envelopment analysis: modeling and computational aspects. *European journal of operational research*, *296*(3), 927–939.

[26] Yang, F., Wang, D., Zhao, L., & Wei, F. (2021). Efficiency evaluation for regional industrial water use and wastewater treatment systems in China: a dynamic interactive network slacks-based measure model. *Journal of environmental management*, *279*, 111721. https://www.sciencedirect.com/science/article/pii/S0301479720316467

[27] Li, H., Zhu, X., & Chen, J. (2020). Total factor waste gas treatment efficiency of China's iron and steel enterprises and its influencing factors: An empirical analysis based on the four-stage SBM-DEA model. *Ecological indicators*, *119*, 106812. https://www.sciencedirect.com/science/article/pii/S1470160X20307500

[28] Liang, L., Yang, F., Cook, W. D., & Zhu, J. (2006). DEA models for supply chain efficiency evaluation. *Annals of operations research*, *145*, 35–49.

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Identifying Effective Factors of Organizational Resilience: A Meta-Synthesis Study

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Abstract

All organizations inevitably must deal with various critical situations. This requires providing the necessary resilience-building infrastructure and facilities. A review of the research literature reveals that scholars have examined factors affecting Organizational Resilience (OR) from different perspectives. This paper aims to compile and synthesize qualitative findings of previous research to gain an in-depth understanding and provide a list of effacing factors to organizations on their improvement practices related to OR. In conducting a systematic literature review, 98 articles were selected for final analysis. The data were analyzed, summarized, and synthesized in a step-by-step coding process, where 14 themes were identified as factors influencing OR. The identified factors included flexibility, control, redundancy and resources, planning and preparedness, decision-making, social capital, resilience policymaking, organizational culture, staff, financial and economic viability, collaboration, customers and markets, modernization discourse, and learning. Through a meta-synthesis of qualitative findings, this study is one of the first to form a novel perspective for offering a holistic understanding of affecting factors that provide evidence to support improvement practices in OR.

Keywords: Resilience, Organizational resilience, Meta-synthesis, Effective factors, Qualitative research.

1 | Introduction

Regardless of size, all organizations are vulnerable to external threats and disasters. Accordingly, even small threats and everyday events can influence the performance of organizations [1]. Because these threats are unavoidable, organizations must be flexible in responding to them. Flexibility (in its general manner) of organizations in the face of external threats has been interpreted as resilience in various sources. The adverse impact of natural disasters and economic crises on organizational operations highlights the need for further study of Organizational Resilience (OR) [2]. Many researchers have recently studied the concept of OR. In addition, the term resilience has been defined differently by several theorists. Scholars have generally assessed and defined resilience from the perspective of organizational capabilities, capacities, characteristics, results, processes, behaviors, strategies, approaches, performance, etc. [3].

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Sutcliffe and Vogus [4] define resilience as a process leading to organizational flexibility and yielding positive results. According to them, resilience indicates how an organization deals with various adversities to achieve a flexible and satisfactory result. Sekaran et al. [5] define OR as the ability and capacity of organizations to cope with various crises and challenges and to return to normal conditions in critical situations. They also argue that all businesses must be resilient. In today's uncertain conditions and changing environment, organizations face countless challenges; therefore, flexibility and adaptability are necessary for all organizations to develop a strong mindset [1]. Organizations would recognize the importance of OR if their work processes were disrupted by unforeseen crises such as the resignation of their knowledge workers [2].

A review of the research literature reveals that scholars have examined factors affecting OR in critical situations from different perspectives. For example, some researchers have focused on organizational viewpoints such as organizational structure and production line flexibility [6]–[8], while others have emphasized individual aspects such as employee attitudes and human resources [1], [9]. On the other hand, some researchers have examined OR from the perspective of organizational environments, such as the geographic location of an organization [10]. By further reviewing the related literature, we see the variety of findings, views, and orientations regarding the effective factors. Researchers have argued that their research results can greatly impact the organization's resilience, and it is required to pay attention to them in the improvement programs. This wide and diverse range of effective factors makes it necessary to have a coherent and concise combination. This study conducted a qualitative meta-synthesis approach to identify factors affecting OR from a holistic point of view. Thus, the research's main problem is identifying the factors that contribute to OR. This study offers a novel perspective and a holistic understanding of the factors influencing OR improvement practices, supported by evidence.

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2 | Theoretical Foundations and Research Background

2.1 | Theoretical Foundations

In the literature, disruptive events and shocks are mentioned using words such as rare events, catastrophes, surprises, and crises. They can be categorized according to the type of event, time, and occurrence inside\outside of the organization, frequency, and length of the event. Furthermore, 'crisis' may be considered a pervasive term for those unexpected events hindering or barricading achieving desired performance and strategic goals [11].

The term resilience refers to the elastic property of materials. The word comes from physics and means "jumping back". In fact, resilient organizations are able to bounce back [2]. Moin Encyclopedic Dictionary defines resilience as the ability to "tolerate" or "withstand". It also considers "stability" and "resistance" as synonyms for the word resilience [6]. The resilience literature generally assesses an organization's ability to adapt to shocks or gradual environmental changes [12]. The word resilience is derived from the Latin verb resilire. It was first introduced into the environmental literature by Holling [13]. In his view, resilience is a measure of a system's ability to absorb change while maintaining the same level of resistance [14].

Resilience is primarily an expression of a point of view and a coping mechanism that helps individuals and organizations understand their surrounding environment and quickly resume their activities [15]. The concept of resilience can be considered from technical, organizational, economic, and social perspectives [6]. Neise et al. [12] argue that the concept of resilience can be analyzed at three levels, including the micro level (i.e., the resilience of independent organizations), the meso level (i.e., the resilience of an industry or a market), and the macro level (i.e., the resilience of a set of organizations and markets). In this study, we seek resilience at the organization (micro) level.

OR is may be defined in three ways: 1) the ability of an organization to absorb pressures and maintain and improve its performance despite existing difficulties and problems, 2) the ability of an organization to return to its original state after an adverse event, and 3) not only to restoration but also to the development of new capabilities and creation of new opportunities for progress [2], [6], [16]. In critical situations, OR provides a balanced state to allow a quick return to a new stable state. Indeed, resilience implies rapid change rather than simply restoring the previous state [17].

2.2 | Research Background

At the organizational level, resilience is trackable through a potion of characteristics, routines, capacities, practices, capabilities, abilities, and processes that facilitates an organization to cope with expected and unexpected disruptions and survive [3], [18]. Many researchers have examined the issue of OR in Iran and other countries. Ebrahimi et al. [6] performed a comprehensive analysis of factors affecting OR of SMEs and ranked the identified factors using the Analytic Hierarchy Process (AHP) technique. Amiri et al. [1] adopted a mixed-methods research approach to develop a model of OR. The authors argued that the designed model could identify the strengths and weaknesses of organizations in the area of resilience. In another research, Kowsar et al. [2] used a quantitative research approach to identify components and consequences of resilience at the individual level among employees of Iran's Cultural Heritage Organization. Mohammadi Shahroodi et al. [16] adopted the grounded theory approach to present a OR model in manufacturing companies.

Rose [7] used mathematical and quantitative models to assess the economic resilience of organizations to natural and man-made disasters. Somers [19] used a quantitative approach to measure the resilience potential of organizations. In the end, he devised an adaptive strategy for organizational crisis planning. In a quantitative survey, Lee et al. [20] developed a tool to measure and compare OR. In analytical research, Sabatino [21] examined the resilience and competitiveness of some organizations and companies. Brown et al. [22] used a quantitative research approach to assess the OR of critical infrastructure providers. In another qualitative study, Duchek et al. [23] formulated a theoretical framework to investigate the impact of divergence and diversity on OR.

In recent years, many studies have examined resilience to COVID-19 and assessed strategies adopted by organizations to deal with this crisis. For example, Bassett et al. [24] examined the initial lessons learned from the COVID-19 crisis in fisheries supply chains. In addition, Marusak et al. [25] examined the resilience of the food supply chain and enumerated lessons that can be learned from the COVID-19 pandemic. In another study, Wieczorek-Kosmala [26] examined the resilience of the tourism industry during the COVID-19 pandemic. Therefore, all studies mentioned above generally examined factors that promote OR.

Researchers have concluded that the concept of OR is multidimensional and has a complex and dynamic nature. Hence it should be characterized via various features and factors [3], [18]. An issue related to current theoretical and empirical findings is that they may have a significant distance from sufficient exploring factors directed to OR [27]. The construct of the literature has passed its infancy but is not mature [3]; it seems to be an appropriate time to conduct a systematic review and meta-synthesis to get a holistic perspective.

3 | Research Method

"A paradigm is a worldview or framework through which knowledge is filtered; it is a foundational perspective carrying a set of assumptions that guide the research process" [28]. There exists a close association between interpretive paradigm and qualitative methodology. Based on the expression of various scholars, it is theoretically recognized that the interpretive paradigm shows the world through the participant's experiences and perceptions to researchers; hence it prefers to use qualitative methods for data gathering [29]. Gadamer realizes three concepts to address the interpretive process: the hermeneutic circle, the fusion of horizons, and a dialogue with the text. This way of understanding through the interpretive process is useful for associating qualitative meta-synthesis with the interpretive paradigm [30].

Critics argue that while individual qualitative researches create rich findings and insights, the lack of linkage between studies restricts their utility [31]. The rapid increase volume of qualitative research has drawn attention to synthesis as one means of combining knowledge gathered from individual studies and developing theory [32].

"Qualitative meta-synthesis serves as a design to interpret and synthesize qualitative findings across individual studies. More than a broad summary, meta-syntheses do not aim merely to summarize all available data; rather, qualitative meta-syntheses present new perspectives on topics through interpreting findings from different qualitative studies to create 'third-level' findings for the advancement of both knowledge and theory" [31]. A meta-synthesis approach is based on a systematic review of the research literature in which researchers analyze documents and articles related to a specific area or topic [33], [34].

Assembling the findings of multiple primary qualitative findings of studies using a systematic process may have several additional benefits, which may help to generate more comprehensive and generalizable theories, identify research gaps, add breadth of understanding to existing knowledge, present novel perspectives via interpreting findings, usefully inform the implementation of interventions and programs and provides evidence to support practice [31], [33], [35], [36].

The authors used the seven-step approach of Sandelowski and Barroso [37] to solve the research problem. This qualitative research adopted an interpretive paradigm approach to explain and interpret the concept of OR and its components. As shown in *Fig. 1*, the following seven steps were taken to achieve the research objectives:

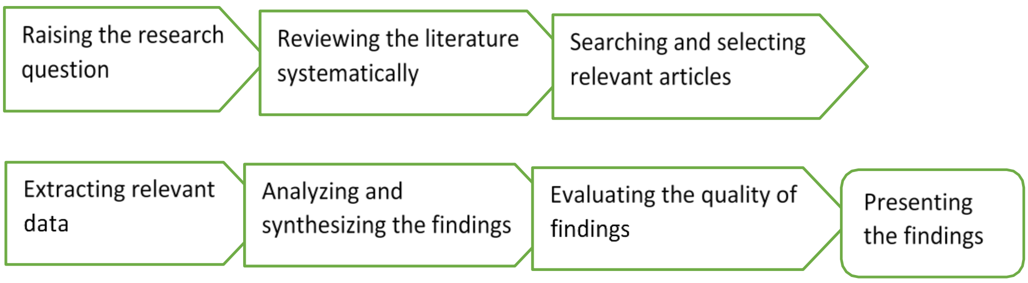

Fig. 1. Seven steps of the meta-synthesis [37].

4 | Findings

The following steps were taken to carry out this research and present its findings.

Step 1. In the first step, the research questions were raised according to the criteria of "what", "who", "when", and "how". *Table 1* explains the research questions in detail.

Table 1. Research questions.

Criterion	Question	Possible Answer
What	What factors affect OR?	To answer this question, the identified codes were categorized and summarized in a step-by-step coding process. Then, factors affecting OR were presented in the findings section (Step 7).
Who	Who does the study population include?	The authors carefully reviewed and screened relevant research articles published in reputable local and international journals and publications, as articles are more scientifically credible than other documents such as books, dissertations, and gray literature sources (usually unavailable to the public).

Table 1. Continued.

Criterion	Question	Possible Answer
When	When were the collected documents and articles written?	In domestic databases, relevant articles published since 2011 were reviewed, while in international databases, relevant articles published since 2000 were reviewed. Relevant articles were screened and selected in January 2022.
How	How do the authors solve the research problem?	In this qualitative study, the authors used a seven-step Sandelowski and Barroso [37] meta-synthesis approach to identify factors affecting OR.

Step 2. After determining the above research questions, the authors collected relevant articles. To this end, the most reputable domestic databases (e.g., Elmnet[1], Magiran[2], and Noormags[3]) and international databases (e.g., Google Scholar, Science Direct, Emerald, Scopus, Web of Science) were searched. *Table 2* shows these reputable databases and the keywords used in the search process.

Table 2. Databases and keywords.

Database	Keyword
Elmnet, Magiran, Noormags, Google Scholar, Emerald, Scopus, Web of Science, and Science Direct	"Resilience", "OR", "Resilience + Organization", "Effective Factors + Resilience", "Impact + Resilience", "Effective Factors+ OR", "Impact + OR", "Model + Resilience", "Model+ OR"

Step 3. Systematic search of the electronic databases was conducted in January 2022 using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) principles (*Fig. 2*).

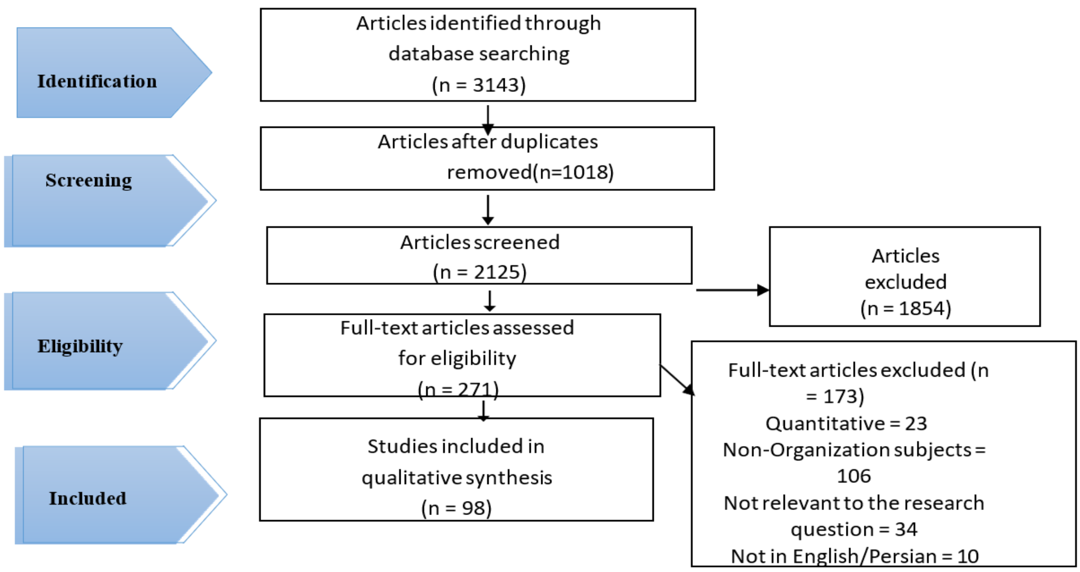

Fig. 2. Article selection process.

Aggregating two types of eligibility, related to topic and research characteristics, the inclusion/exclusion criteria can be realized as follow: related topic, language, publication year, document type, peer-review status, funding, and methodology [38]. The inclusion/exclusion criteria of this study is given in *Table 3*. Therefore, among the initially selected articles (N = 3143), 98 articles were identified for the final analysis.

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[1] https://www.elmnet.ir/
[2] https://www.magiran.com/
[3] https://www.noormags.ir/

Table 3. Eligibility criteria.

Inclusion	Exclusion
Research article	Quantitative funding
Were peer-reviewed	Not organization subject
Qualitative research or the qualitative part of a mixed methods study	Not related to research questions
	Not in English/Persian
Explicit or implicit mention of factors effacing OR	
English/Persian language	
Published from 2000 to January 2022	

There is the variety of appraisal tools for the quality assessment of qualitative research. The chosen appraisal tool depends on the aims of the finding's synthesis, the researcher's expertise, and the time and resources available. We chose Critical Appraisal Skills Programme (CASP) checklist for qualitative research to appraise the quality of included studies since it: 1) is short and easy-to- follow, 2) applies to all qualitative methodologies and 3) is most commonly used in qualitative synthesis [39]. Quality appraisal was completed by YH and MA and adjudicated by the rest of the authors. All studies were included regardless of methodological quality to avoid excluding important descriptive findings due to methodological weakness.

Steps 4 and 5. This study used the Unlu-Qureshi instrument as an analytic tool for analyzing and coding data. It comprises four consecutive data analysis steps, including developing codes, concepts, categories, and themes in sequence. Through the cyclic procedure, it can be used in all three stages open, selective (axial), and theoretical coding. The step-by-step approach of the Unlu-Qureshi instrument over the three coding stages benefits the analytical process in multiple ways as helping in organizing the data, decreasing researchers' block, strengthening the verification of the findings (helping with frequent interaction and familiarity with data), and allowing freedom to researchers by informing them of requisite steps [40].

Despite the final result of qualitative meta-synthesis as an integration of research findings, researchers may use a variety of approaches to synthesize findings. It is related to the purpose and desired result of research and the kind of findings in the reports included in the study. We decided to apply taxonomic analysis to synthesize our findings because it: 1) is an inductive form of domain analysis useful for theory development, 2) is to a great extent compatible with the axial and selective coding, and 3) allows more penetrating syntheses by showing what is not there that ought logically to be there, in addition to the explicit theoretical properties of findings [37]. In the initial (open) coding process, the researchers first extracted 814 codes; however, after correcting these codes based on expert opinions and omitting duplicate and overlapping items, 112 concepts were identified. These 112 concepts were classified into 44 categories and 14 themes using the taxonomy approach and Unlu-Qureshi tool (*Table 4*). This task was done in a cyclic process and in consultation with two academic experts and a resilience practitioner to enhance validity.

Table 4. Initial codes, concepts, categories, and themes.

Theme	Category	Concept	Number of Concepts	Author(S)
Flexibility	Flexibility in operation and structure	The flexibility of production line and operation based on market requirements	13	[18], [19], [56], [63], [64],[66],
		Flexibility of organizational structure	10	[69], [74], [80], [90],
		Compatibility with laws and natural resources	9	[102]
	Robustness	Appropriate design (resistance and absorption of shocks)	6	[1], [7], [9], [42], [47], [61]
		Recruitment of resilient employees	2	
	Dynamic competitiveness	Agility (acting quickly in crises and finding alternatives to deploy in times of crisis)	12	[7], [8], [19], [50], [105], [110], [79],
		Competitive orientation	3	[47], [80],
		Sensitivity to market risk	3	[51], [93], [62]

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Table 4. Continued.

Theme	Category	Concept	Number of Concepts	Author(S)
Control	Appropriate performance evaluation	Developing an evaluation checklist containing resilience indicators	5	[8], [46], [48], [49], [57], [88]
		Compatibility of performance evaluation mechanism with the complex nature of systems	3	
	Risk assessment and management	Evaluation and implementation of relevant risk management standards in all areas (financial, market, technical, safety and environmental)	10	[48], [50] [57], [61], [62], [64] [81] [1], [8], [15] [20], [22]
	Monitoring and anticipating	Regular monitoring of operational status and early detection of disruptive events within the organization	18	[48], [49], [52], [55], [58], [67], [68], [69], [70], [71],
		Proactiveness and managerial and market information seeking	19	[62], [65] [66]
		Reinforcement of the culture of reporting	4	
Awareness and proper perception of crisis		Understanding and analyzing critical situations, their consequences, and responsibilities in times of crisis	7	[8], [9], [19], [72], [73] [68]
		Obtaining information about legal requirements and structures (to identify potential barriers to necessary organizational changes)	1	
		Noticing the impact of different departments on each other	1	
Redundancy and resources	Revenue diversity	Strategic investments to increase revenue diversity	5	[55], [74], [75], [70], [76], [77], [78]
		Diversity of products and target markets	6	[1], [8], [12], [20], [22],
	Diversity of access to resources	Effective internal and external communication channels	16	[61], [79], [80], [72], [81], [65], [48], [52], [56],
		Information sources	16	[57], [58], [82],
		Access to new technologies	14	[68], [69], [83],
		Access to material resources	16	[84], [74], [85],
		Access to financial resources and tools such as loans	23	[86], [77], [71], [87]
		Access to experts inside and outside the organization	25	[22], [63], [80], [57], [67], [74], [71], [78]
	Reserves and emergency access	Financial reserves	4	
		Precautionary storage of raw materials, spare parts and final products	4	
		Manpower reserves in key positions	4	
		Other resources in times of crisis	2	[10], [15], [24], [53], [61]
	Locational characteristics	Ability to localize the supply chains	2	
		Geographical proximity in terms of access to markets and operational advantages	4	
	Operational redundancy	Redundancy of production capacity	8	[8], [12], [24],
		Redundancy of storage capacity	7	[88], [52], [58],
		Redundancy (diversity) of suppliers and contractors	6	[42], [89], [67], [69], [83], [77]
		Redundancy and diversity of distribution channels	8	

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Table 4. Continued.

Theme	Category	Concept	Number of Concepts	Author(S)
Planning and preparedness	Managing vulnerabilities	Innovative use of insurance	6	[1], [20], [22], [61], [80], [62], [81], [65], [48], [59], [83], [75]
		Management of vulnerabilities and emergencies	7	
		Prioritization of tasks and equitable distribution of resources in times of crisis	6	
	Applying planning strategies	Integrating operations planning and ensuring business continuity	10	[8], [19], [20], [22], [61], [83], [65], [46], [48], [52], [55], [67], [70], [71], [64]
		Considering alternative scenarios for different situations	20	
	Maintaining preparedness	Preparing and organizing to handle crises	14	[1], [61], [79], [80], [83], [73], [58], [84], [71]
		Holding resilience exercises and training	8	
Decision making	Inclusive decision making	Promoting decentralized decision making and employee involvement	8	[9], [19], [20], [49], [50], [52], [55], [57], [58], [59], [89], [82], [68], [70], [86], [87]
		Delegating authority and reinforcing management autonomy	8	
		Encouraging participation of other stakeholders in decision making and planning	6	
	Smart and transparent decision making	Making decisions based on up-to-date data analysis	10	[8], [9], [20], [80], [72], [62], [73], [46], [50], [57], [60], [68], [69], [90], [87], [71]
		Obtaining expert opinions and accepting their recommendations	5	
		Encouraging transparency of roles and responsibilities	7	
Social capital	Networking and gaining public support	Government and household supports	5	[6], [16], [26], [92], [52], [53], [58], [59], [67], [93], [77], [5]
		Information sharing and public relations management	6	
		Participation in social affairs	9	
	Measurement of social responsibility with KLD-400 social index	Measurement of social responsibility with KLD-400 social index	1	[43]
Resilience policymaking	Leadership and commitment to resilience	Intention and commitment (alignment with goals and motivations)	11	[1], [20], [61], [83], [65],
		Transformational leadership (strengthening communication and teamwork among employees)	16	[66], [88], [46], [48], [93], [52], [54], [58], [60], [93], [86], [90], [5], [71], [94], [95]
	Resilience policy	Adopting diverse approaches to achieve resilience	8	
		Creating a balance between goals and a balance between redundancy and productivity	2	
		Setting organization's risk appetite at a modest level	2	
	Strategic management	Strategic thinking and planning	9	[1], [61], [63], [72], [49], [43], [67], [98]
		Diversity of skills and management methods (e.g. performance and change management)	9	[6], [12], [61], [93], [62], [65], [46], [51], [53], [56], [64],[94]

Table 4. Continued.

Theme	Category	Concept	Number of Concepts	Author(S)
Organizational culture	Commitment and integrity	Internal and external integration (development of intra- and extra- organizational collaboration and information sharing)	8	[46], [55], [61], [89], [99], [98], [47], [90], [88]
		Commitment and assurance to employees and partners	6	
		Acceptance of conflict and application of normative control	2	
	Informal procedures and responses	Informal procedures and diversity of work processes	2	[20], [86], [100]
		Sensitivity and rapid response to problems and changes	3	
	A collective approach to resilience	A shared vision of resilience	8	[8], [16], [20], [61], [50], [58], [67], [98], [71]
		Common resilience goals	4	
Staff	Evaluation and motivation	Incentives (e.g., a sense of worth, job security, and financial rewards)	16	[8], [16], [54], [58], [99], [82], [100], [70]
		Continuous staff evaluation	8	
	Cooperation and teamwork	Encouraging cooperation and teamwork	9	[8], [16], [20], [42], [46], [95], [49], [57], [60], [88], [91], [68], [71], [103],[104]
		Developing participation systems	8	
	Multiple competencies and skills	Developing digital and teleworking competencies	3	[3], [9], [61], [105], [95], [101], [106], [92], [72], [84], [77],[88]
		Increasing different qualifications of employees	4	
		Increasing the ability of team members to take on multiple roles	6	
	Individual features	Diversity of demographic and professional characteristics of staff	4	[3], [23], [42],[61], [89], [95], [100], [82], [75], [107], [108]
		Problem-solving, self-awareness, and self-organization abilities	9	
		Psychological resilience (positive thinking, hope, self-confidence, flexibility, and adaptability)	7	
Financial and economic viability	Appropriate pre-crisis conditions	Possession of adequate high-quality tangible assets	9	[12], [16], [26], [50], [59], [112], [51], [92], [110], [111]
		Higher operating profit margin	4	
		Desirable financial ratios	3	
		Suitable operating conditions	3	
	Operation and business model optimization	Company size and economies of scale	2	[8],[16], [55], [102], [75], [112], [111], [98], [62]
		High raw material productivity and energy efficiency	5	
		Continuous revision of competitive strategies and reallocation of resources based on existing opportunities and threats	13	
	Cost and debt management	Business cost structure	2	[15], [24], [26], [50], [62],[75], [85], [76], [77]
		The ability to reduce operating and overhead costs	3	
		Correction of capital structure and expansion of leverage capacity (receiving loans and repaying debts)	3	

Table 4. Continued.

Theme	Category	Concept	Number of Concepts	Author(S)
Collaboration	Outsourcing and partnership	Prioritization of cooperation and outsourcing	7	[12], [20], [25], [59], [83], [75], [86], [76], [77], [5], [71]
		Strategic partnership (being part of a larger coalition)	10	
		Collective response in times of crisis	4	
	Networking and resource sharing	Establishing networks and cooperating with competitors and other organizations	12	[56], [59], [68], [74], [112], [85], [86], [99], [98], [80], [65], [63]
		Sharing resources between partners	8	
Customers and markets	Optimization of sales strategy	Management of economic events and market trends on customer purchase intentions	2	[25], [26], [59], [83], [77]
		Appropriate crisis-oriented sales and marketing policy (maintaining market share or increasing cash flow)	4	
	Market development	Focusing on key markets	3	[85], [111], [80], [70], [73], [113]
		Discovering and developing new markets	4	
	Customer orientation	Interaction with customers	5	[63], [85], [98], [50], [80], [73], [93]
		Product quality and advertising	3	
Modernization discourse	Application of new technologies in all organizational activities	Applying new technologies in production and service Sectors (upgrading physical Assets and infrastructure)	13	[8], [23], [45], [50], [57], [89], [67], [82], [101], [83], [75], [112], [70], [76], [64]
		Applying new technologies in administrative affairs (developing teleworking technologies and digitalization)	10	
	Product development	Developing new products	3	[33], [73], [98], [113]
		Creating added value in the product	2	
	Entrepreneurship and creativity	Reusing resources creatively and creating value from wastes	4	[8], [13], [20], [40], [102], [71], [98], [114]
		Increasing innovative and creative capacities	14	
	Institutionalization of innovation	Investing in research and innovation	4	[52], [57], [68], [69], [70], [115], [64]
		Building a culture of innovation and supporting new ideas	6	
Learning	Knowledge management	Documenting destructive experiences and events	9	[8], [17], [20], [49], [57], [67], [83], [112], [70], [76], [5], [71], [117], [116]
		Updating protocols based on domestic and international knowledge	3	
	Acquisition of necessary skills and qualifications	Obtaining certificates from renowned organizations (e.g. ISO 14001)	3	[9], [57], [75], [64], [114]
		Training employees to increase their qualifications and competencies	11	

Table 4. Continued.

Theme	Category	Concept	Number of Concepts	Author(S)
	Institutionalization of learning	Establishing a culture and passion about learning	6	[1], [16], [105], [40], [46], [49], [52], [59], [82], [86], [84], [74], [87], [78], [99], [116]
		Learning from positive and negative experiences	15	
		Continuous learning from partners' experiences	6	

Step 6. In this step, the quality of the synthesized findings was evaluated through validity and reliability. The following measures have been taken in this study to increase the validity according to the recommendations of Sandelowski and Barroso [37]: 1) documentation of all procedures, 2) consultation with experts in research synthesis and resilience, and 3) independent appraisal of each included article by at least two reviewers [37]. Reliability was investigated as well by calculating the Kappa agreement coefficient. For this purpose, two experts gave their opinions on the coding process. The data were then analyzed in SPSS to calculate the agreement coefficient. According to *Table 5*, the Kappa coefficient was calculated as 0.701 at a significance level of 0.000. Kappa coefficients > 0.6 are acceptable, and values > 0.8 indicate ideal inter-rater agreement [41]. P-value < 0.05; hence, the assumption of independence of the extracted codes is rejected, and the extracted codes have desirable reliability.

Table 5. Calculating the Kappa coefficient.

	Value	Symmetric Measures Asymptotic Standard Errora[a]	Approximate T[b]	Approximate Significance
Measure of agreement Kappa	0.701	0.042	20.268	0.000
No. of valid cases	814			

a. Not assuming the null hypothesis.
b. Using the asymptotic standard error assuming the null hypothesis.

Step 7. Finally, flexibility, control, redundancy and resources, planning and preparedness, decision making, social capital, resilience policymaking, organizational culture, staff, financial and economic viability, collaboration, customers and markets, modernization discourse, and learning were identified as major factors affecting OR. These factors, which are the main findings of the present research, are shown in *Fig. 3*.

Fig. 3. Factors affecting OR.

5 | Discussion

OR has aggressively become a vital feature of survival. Since a review of the research literature revealed that scholars have examined factors affecting OR from different perspectives, the authors did not detect an in-depth understanding of how to boost and improve OR within organizations. Aiming to fill this research gap, they did their best, utilizing broad research articles and conducting qualitative meta-synthesis research. By searching domestic and international databases, 98 articles were finally selected, and by applying the meta-synthesis, 14 effective factors were extracted. Brief descriptions of each of them are as follows:

Flexibility, considered an essential characteristic of today's organizations, has been the subject of many studies. Flexible mechanisms help organizations successfully deal with critical situations, increasing their resilience under different conditions. The three main dimensions of organizational flexibility included flexibility in operations and structure (e.g., flexibility of production line), robustness, and dynamic competitiveness.

Control was another important factor influencing OR. Appropriate organizational control consists of elements of appropriate performance evaluation, risk assessment, and management, effective monitoring and anticipating, and proper perception of a crisis and its consequences.

Redundancy and resources affected OR. This concept means that under normal conditions, excessive capacity and multiple backups are prepared for shortage or emergency [42]. Based on the results, this factor is composed of elements of revenue diversity, diversity of access to resources, reserves and emergency access, suitable geographic location, and operational redundancy (including redundancy of production and storage capacity, multiplicity of suppliers, and redundancy of distribution channels).

Planning and preparedness were found to substantially affect OR. In general, items such as applying planning strategies in organizations, managing vulnerabilities in times of crisis, and maintaining preparedness of all organizational sectors can increase the resilience of organizations and help them cope with critical situations.

Decision making was another important factor that had an impact on OR. Decision making is mentioned in many management books and articles as one of the main tasks of managers. To enhance resilience, the decision making should be inclusive to promote decentralizing and reinforce management autonomy, smart and transparent to gain the experts opinion and apply the updated data analysis.

Social capital was identified as another important factor influencing OR. Organizations can achieve desirable levels of resilience by expanding their networking activities, gaining public support, and fulfilling their responsibilities towards society. The researchers introduced the KLD-400 social index as an important quantitative measure of social capital. This index includes all major aspects of organizations, including environmental, social, and governmental factors [43].

Resilience policymaking includes leadership commitment to resilience, resilience policy, and strategic management as major components that can help organizations overcome various crises. In this regard, transformational leadership that leads to strengthening communication and teamwork among employees, the balance between redundancy and productivity, and management's ability to facilitate change should be considered.

Organizational culture was another critical factor affecting OR. Organizations can enhance their organizational culture in times of crisis through behaviors, beliefs, and norms such as commitment and integrity, informal procedures and responses, and collective approaches to resilience. It is important to be sensitive, rapidly develop alternatives, and have a common vision and goals for resilience.

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Staff was another research finding, and this refers to individual and behavioral characteristics of personnel. Human resources are the most important assets of organizations; therefore, organizations must carefully enhance aspects such as cooperation and teamwork motivation, competencies and skills, and individual resilience. Nowadays, the development of digital skills and the creation of multiple competencies of employees are more paid attention.

Financial and economic viability was also concluded to influence OR. Accordingly, organizations can increase their resilience by creating appropriate pre-crisis conditions, optimizing operations and processes, and managing costs and debt. To fulfill this, in addition to paying attention to productivity and desirable financial ratios, it is vital to continuously revise competitive strategies and reallocate resources based on existing opportunities and threats.

Collaboration can help organizations better manage different crises by enhancing their resilience. The collaboration consisted of outsourcing, networking, and sharing resources with other organizations. Research has shown the need for a coalition and collective response to deal with the crisis.

Customers and markets were found to remarkably affect OR by optimizing sales strategy, market development, and customer orientation. It is crucial to adjust marketing and sales policy regarding any crisis to maintain market share and/or increase cash flow and improve interaction with customers.

Modernization discourse was another factor that had an impact on OR. The main elements of this factor included the application of new technologies in all organizational activities, product development, entrepreneurship and creativity, and institutionalization of innovation. Modernization is not only limited to physical equipment and the production line but also includes all areas such as how to manage the organization, communication and teleworking, data analysis and decision making, and handling problems. So modernization should be done in this field as well; hence the authors used "discourse" to describe it. Furthermore, creativity and entrepreneurship can be a business savior in a crisis, as well as a sustainable competitive advantage.

Learning can increase resilience by promoting knowledge management practices, updating skills and competencies, and institutionalizing a learning culture. Documenting and learning from destructive experiences and events and sharing the lessons with partners is crucial to dealing with crises. Establishing a culture and passion for learning can be advantageous in this respect.

Using an extensive range of literature to explore the multidimensional nature of OR, our research made it clear that a proper composition of affecting factors is essential to achieve resiliency and provided helpful insights into organizing resilience practices. This research provides a deep insight into the effective factors of OR. Applying detailed results (*Table 4*) as a checklist helps policymakers and managers to develop resilience improvement practices and monitor their implementation. Furthermore, they need to determine which plan should be a priority based on lessons learned from previous disruptive events.

The business and activity environment has been faced with competition, complexity, ambiguity, hazards, and continuous change since the last century as yet, therefore causing the emergence and growth of concepts such as robustness and anti-fragility along with resilience, which seek to help managers deal with these risky situations through relatively different manners [44], [45].

Robustness analysis argues there is an appropriate decision that is more stable than others in the face of alternative futures caused by uncertainty [44]. Anti-fragility does not consider failure in responding to change or crisis. According to this point of view, always a solution based on innovation, unplanned, dependent on context and time will be in access [45]. However, resilience associates stability with "flexibility" to mitigate the disruptive consequences of shocks. Furthermore, acknowledging the possibility of vulnerability, it combines creativity with learned lessons from previous failures to develop solutions.

Moreover, according to Maturity Model for OR (MMOR), resiliency develops gradually from a simple to a more complex form, robustness, resilience in the middle, and finally, antifragility [18].

6 | Limitation and Future Research

The current study contributes to the related literature by collecting the various features affecting factors that facilitate OR. Via these fourteen factors extracted, improvement practices might be more efficiently exploited in fulfilling different tasks in the OR process in an organization. Despite this, the study has certain limitations. First, this study develops an in-depth understanding of the effective factors of OR but provides no empirical support for it. Second, the findings of this study are finite, but OR research and practices about it are dynamic. Furthermore, this study just focuses on research articles that are online accessible, while there are other reports and case studies that are not generally available but might be helpful to understanding resilience. Third, monitoring newly published papers related to the research was not considered before finalizing the synthesis.

According to the findings, limits, and theoretical background of this paper, our future research streams suggestions are as follows:

- *Validating the affecting factors via empirical research using various methods such as case studies and surveys and improving them based on practical feedback.*
- *Updating the list of effective factors by applying both primary and secondary research using the newest published articles along with gray literature (in case of accessible and authentic scientifically).*
- *Exploring mutual relationships between affecting factors to find how those can be synergized within an organization.*
- *Categorizing the affecting factors in terms of their associations with different stages of the conceptual models, namely Duchek* [11]*, to identify and validate which set of factors is appropriate for particular tasks and necessities of the different OR process stages.*
- *Conducting the same methodology to related concepts such as robustness, anti-fragility, and agility since this study highlights the usefulness of a meta-synthesis strategy toward an in-deep understanding of how organizations can deal with and survive against shocks and disruptive events.*

7 | Conclusion

To gain an in-depth understanding and provide a list of effacing factors to organizations on their improvement practices related to OR, this paper aims to compile and synthesize qualitative findings of previous research. While it is widely acknowledged that OR is crucial for facing and passing shocks, it is approximately equally recognized as a challenging and multiple issue. Through a meta-synthesis of qualitative findings, this study is one of the first to form a novel perspective for offering a holistic understanding of affecting factors that provide evidence to support improvement practices in OR.

References

[1] Amiri, M., Olfat, L., Feyzi, K., & Salehi Abarquee, M. A. (2018). Designing a model for organizational resilience. *The journal of productivity management*, *11*(44), 35–65. (**In Persian**). https://elmnet.ir

[2] Kowsar, Z., Nedaei, A., & Seyednaghavi, M. (2019). Effective factors and consequences of organizational resilienceno title. *Journal of management research in iran*, *23*(4), 1–22. (**In Persian**). https://mri.modares.ac.ir/article_508.html?lang=en

[3] Hillmann, J., & Guenther, E. (2021). Organizational resilience: a valuable construct for management research? *International journal of management reviews*, *23*(1), 7–44. DOI:10.1111/ijmr.12239

[4] Sutcliffe, K. M. (2003). Organizing for resilience. In *Positive organizational scholarship: foundations of a new discipline* (pp. 94–110). Berrett-Koehler Publishers.

Hamidavi Nasab et al.| Int. J. Res. Ind. Eng. 12(2) (2023) 177-196

[5] Sekaran, U., Lai, L., Ussiri, D. A. N., Kumar, S., & Clay, S. (2021). Role of integrated crop-livestock systems in improving agriculture production and addressing food security – a review. *Journal of agriculture and food research*, *5*, 100190. DOI:10.1016/j.jafr.2021.100190

[6] Ebrahimi, S. A., Feyz, D., & Chitkaran, H. (2017). A comprehensive analysis of factors influencing organizational resilience of SMEs. *ORMR*, *7*(3), 37–58. (**In Persian**). https://ormr.modares.ac.ir/article-28-5473-fa.html

[7] Rose, A. (2007). Economic resilience to natural and man-made disasters: multidisciplinary origins and contextual dimensions. *Environmental hazards*, *7*(4), 383–398. DOI:10.1016/j.envhaz.2007.10.001

[8] Iftikhar, A., Purvis, L., & Giannoccaro, I. (2021). A meta-analytical review of antecedents and outcomes of firm resilience. *Journal of business research*, *135*, 408–425. DOI:10.1016/j.jbusres.2021.06.048

[9] Izadi, H. (2018). Identifying factors reducing resilience of organizations in critical situations with AHP modeling (case study: Amol fire department). *Disaster prevention and management knowledge*, *7*(4), 307–319. (**In Persian**). https://dpmk.ir/article-1-149-fa.html

[10] Teerasoponpong, S., & Sopadang, A. (2022). Decision support system for adaptive sourcing and inventory management in small- and medium-sized enterprises. *Robotics and computer-integrated manufacturing*, *73*, 102226. DOI:10.1016/j.rcim.2021.102226

[11] Duchek, S. (2020). Organizational resilience: a capability-based conceptualization. *Business research*, *13*(1), 215–246. https://doi.org/10.1007/s40685-019-0085-7

[12] Neise, T., Verfürth, P., & Franz, M. (2021). Rapid responding to the COVID-19 crisis: assessing the resilience in the German restaurant and bar industry. *International journal of hospitality management*, *96*, 102960. DOI:10.1016/j.ijhm.2021.102960

[13] Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual review of ecology and systematics*, *4*(1), 1–23.

[14] Ghanbary, S., Salavatian, S., & Kia, A. A. (2019). Resilience of news organizations in natural crises:" conscious alive humane" metaphor. *Disaster prevention and management knowledge (quarterly)*, *8*(4), 321–338.

[15] Mithani, M. A., Gopalakrishnan, S., & Santoro, M. D. (2021). Does exposure to a traumatic event make organizations resilient? *Long range planning*, *54*(3), 102031. DOI:10.1016/j.lrp.2020.102031

[16] Mohammadi Shahroodi, H., Rahimnia, F., Malekzadeh, Gh., & Khorakian, A. R. (2019). Presentation of organizational resilience pattern in manufacturing companies with using the grounded theory approach. *Public management researches*, *12*(43), 111–134. (**In Persian**). https://jmr.usb.ac.ir/article_4745.html?lang=en

[17] Jiang, Y., Ritchie, B. W., & Verreynne, M. L. (2021). Developing disaster resilience: a processual and reflective approach. *Tourism management*, *87*, 104374. DOI:10.1016/j.tourman.2021.104374

[18] Ruiz-Martin, C., López-Paredes, A., & Wainer, G. (2018). What we know and do not know about organizational resilience. *International journal of production management and engineering*, *6*(1), 11–28.

[19] Somers, S. (2009). Measuring resilience potential: an adaptive strategy for organizational crisis planning. *Journal of contingencies and crisis management*, *17*(1), 12–23. DOI:10.1111/j.1468-5973.2009.00558.x

[20] Lee, A. V., Vargo, J., & Seville, E. (2013). Developing a tool to measure and compare organizations' resilience. *Natural hazards review*, *14*(1), 29–41. DOI:10.1061/(asce)nh.1527-6996.0000075

[21] Sabatino, M. (2016). Economic crisis and resilience: resilient capacity and competitiveness of the enterprises. *Journal of business research*, *69*(5), 1924–1927. DOI:10.1016/j.jbusres.2015.10.081

[22] Brown, C., Seville, E., & Vargo, J. (2017). Measuring the organizational resilience of critical infrastructure providers: a New Zealand case study. *International journal of critical infrastructure protection*, *18*, 37–49.

[23] Duchek, S., Raetze, S., & Scheuch, I. (2020). The role of diversity in organizational resilience: a theoretical framework. *Business research*, *13*(2), 387–423. DOI:10.1007/s40685-019-0084-8

[24] Bassett, H. R., Lau, J., Giordano, C., Suri, S. K., Advani, S., & Sharan, S. (2021). Preliminary lessons from COVID-19 disruptions of small-scale fishery supply chains. *World development*, *143*, 105473. DOI:10.1016/j.worlddev.2021.105473

[25] Marusak, A., Sadeghiamirshahidi, N., Krejci, C. C., Mittal, A., Beckwith, S., Cantu, J., … Grimm, J. (2021). Resilient regional food supply chains and rethinking the way forward: key takeaways from the COVID-19 pandemic. *Agricultural systems*, *190*, 103101. DOI:10.1016/j.agsy.2021.103101

[26] Wieczorek-Kosmala, M. (2022). A study of the tourism industry's cash-driven resilience capabilities for responding to the COVID-19 shock. *Tourism management*, *88*, 104396. DOI:10.1016/j.tourman.2021.104396

[27] Linnenluecke, M. K. (2017). Resilience in business and management research: a review of influential publications and a research Agenda. *International journal of management reviews*, *19*(1), 4–30.

[28] Leavy, P. (2017). *Research design: quantitative, qualitative, mixed methods, arts-based, and community-based participatory research approaches*. The Guilford Press.

[29] Thanh, N. C., & Thanh, T. T. (2015). The interconnection between interpretivist paradigm and qualitative methods in education. *American journal of educational science*, *1*(2), 24–27.

[30] Zimmer, L. (2006). Qualitative meta-synthesis: a question of dialoguing with texts. *Journal of advanced nursing*, *53*(3), 311–318. DOI:10.1111/j.1365-2648.2006.03721.x

[31] Nye, E., Melendez-Torres, G. J., & Bonell, C. (2016). Context and implications document for: origins, methods and advances in qualitative meta-synthesis. *Review of education*, *4*(1), 80–83.

[32] Britten, N., Campbell, R., Pope, C., Donovan, J., Morgan, M., & Pill, R. (2002). Using meta ethnography to synthesise qualitative research: a worked example. *Journal of health services research and policy*, *7*(4), 209–215.

[33] Mohammed, M. A., Moles, R. J., & Chen, T. F. (2016). Meta-synthesis of qualitative research: the challenges and opportunities. *International journal of clinical pharmacy*, *38*(3), 695–704.

[34] Kamali, Y. (2017). The methodology of meta synthesis and implications for public policy. *Politics quarterly*, *47*(3), 721–736. (**In Persian**). https://jpq.ut.ac.ir/article_62861.html

[35] Hannes, K., & Lockwood, C. (2012). *Synthesizing qualitative research: choosing the right approach*. John Wiley & Sons.

[36] Atkins, S., Lewin, S., Smith, H., Engel, M., Fretheim, A., & Volmink, J. (2008). Conducting a meta-ethnography of qualitative literature: Lessons learnt. *BMC medical research methodology*, *8*(1), 1–10.

[37] Sandelowski, M., & Barroso, J. (2006). *Handbook for synthesizing qualitative research*. Springer publishing Company.

[38] Xie, J., Ke, Q., Cheng, Y., & Everhart, N. (2020). Meta-synthesis in library & information science research. *Journal of academic librarianship*, *46*(5), 102217. DOI:10.1016/j.acalib.2020.102217

[39] Majid, U., & Vanstone, M. (2018). Appraising qualitative research for evidence syntheses: a compendium of quality appraisal tools. *Qualitative health research*, *28*(13), 2115–2131. DOI:10.1177/1049732318785358

[40] Qureshi, H. A., & Ünlü, Z. (2020). Beyond the paradigm conflicts: a four-step coding instrument for grounded theory. *International journal of qualitative methods*, *19*, 1609406920928188. DOI:10.1177/1609406920928188

[41] Mohammad Beigi, A., Mohammad-Salehi, N., & Aligol, M. (2015). Validity and reliability of different measurement tools in applied health research. *Journal of Rafsanjan university of medical sciences*, *13*(12), 1153–1170. (**In Persian**). http://journal.rums.ac.ir/browse.php?a_code=A-10-1899-1&sid=1&slc_lang=fa

[42] Azadeh, A., Salehi, V., Ashjari, B., & Saberi, M. (2014). Performance evaluation of integrated resilience engineering factors by data envelopment analysis: the case of a petrochemical plant. *Process safety and environmental protection*, *92*(3), 231–241. DOI:10.1016/j.psep.2013.03.002

[43] Ortiz-de-Mandojana, N., & Bansal, P. (2016). The long-term benefits of organizational resilience through sustainable business practices. *Strategic management journal*, *37*(8), 1615–1631. DOI:10.1002/smj.2410

[44] Sorourkhah, A., Azar, A., Babaie-Kafaki, S., Shafiei-Nikabadi, M., & Author, C. (2018). Using weighted-robustness analysis in strategy selection (case study: Saipa automotive research and innovation center). *Industrial management journal*, *9*(4), 665–690. DOI:10.22059/imj.2018.247856.1007361

[45] Danchin, A., Binder, P. M., & Noria, S. (2011). Antifragility and tinkering in biology (and in business) flexibility provides an efficient epigenetic way to manage risk. *Genes*, *2*(4), 998–1016.

[46] Cantu, J., Tolk, J., Fritts, S., & Gharehyakheh, A. (2021). Interventions and measurements of highly reliable/resilient organization implementations: a literature review. *Applied ergonomics*, *90*, 103241. DOI:10.1016/j.apergo.2020.103241

[47] Kantur, D., & Say, A. I. (2015). Measuring organizational resilience: a scale development. *Pressacademia*, *4*(3), 456–456. DOI:10.17261/pressacademia.2015313066

[48] Bragatto, P., Vairo, T., Milazzo, M. F., & Fabiano, B. (2021). The impact of the COVID-19 pandemic on the safety management in Italian Seveso industries. *Journal of loss prevention in the process industries*, *70*, 104393. DOI:10.1016/j.jlp.2021.104393

[49] Peñaloza, G. A., Torres Formoso, C., & Abreu Saurin, T. (2021). A resilience engineering-based framework for assessing safety performance measurement systems: a study in the construction industry. *Safety science*, *142*, 105364. DOI:10.1016/j.ssci.2021.105364

Hamidavi Nasab et al.| Int. J. Res. Ind. Eng. 12(2) (2023) 177-196

[50] Andersson, T., Cäker, M., Tengblad, S., & Wickelgren, M. (2019). Building traits for organizational resilience through balancing organizational structures. *Scandinavian journal of management*, *35*(1), 36–45.

[51] Schmid, B., Raju, E., & Jensen, P. K. M. (2021). COVID-19 and business continuity - learning from the private sector and humanitarian actors in Kenya. *Progress in disaster science*, *11*, 100181. DOI:10.1016/j.pdisas.2021.100181

[52] Pashapour, S., Bozorgi-Amiri, A., Azadeh, A., Ghaderi, S. F., & Keramati, A. (2019). Performance optimization of organizations considering economic resilience factors under uncertainty: a case study of a petrochemical plant. *Journal of cleaner production*, *231*, 1526–1541.

[53] Herbane, B. (2019). Rethinking organizational resilience and strategic renewal in SMEs. *Entrepreneurship and regional development*, *31*(5–6), 476–495. DOI:10.1080/08985626.2018.1541594

[54] Cooke, F. L., Wood, G., Wang, M., & Li, A. S. (2021). Riding the tides of mergers and acquisitions by building a resilient workforce: a framework for studying the role of human resource management. *Human resource management review*, *31*(3), 100747. DOI:10.1016/j.hrmr.2020.100747

[55] Bahri Korbi, F., Ben-Slimane, K., & Triki, D. (2021). How do international joint ventures build resilience to navigate institutional crisis? the case of a Tunisian-French IJV during the Arab-Spring. *Journal of business research*, *129*, 157–168. DOI:10.1016/j.jbusres.2021.02.059

[56] Sayahpour, A., Hematiyan, F., & Shoul, A. (2019). An analysis of organizational resilience process with interpretive structural modeling technique (case study: Sapco). *Journal of iranian public administration studies*, *2*(1), 123–147. (**In Persian**). https://www.jipas.ir/article_90667.html?lang=fa

[57] Patriarca, R., Di Gravio, G., Costantino, F., Falegnami, A., & Bilotta, F. (2018). An analytic framework to assess organizational resilience. *Safety and health at work*, *9*(3), 265–276. DOI:10.1016/j.shaw.2017.10.005

[58] Barasa, E., Mbau, R., & Gilson, L. (2018). What is resilience and how can it be nurtured? a systematic review of empirical literature on organizational resilience. *International journal of health policy and management*, *7*(6), 491–503. DOI:10.15171/ijhpm.2018.06

[59] Cradock-Henry, N. A., & Fountain, J. (2019). Characterising resilience in the wine industry: Insights and evidence from Marlborough, New Zealand. *Environmental science and policy*, *94*, 182–190.

[60] Cotta, D., & Salvador, F. (2020). Exploring the antecedents of organizational resilience practices – a transactive memory systems approach. *International journal of operations and production management*, *40*(9), 1531–1559. DOI:10.1108/IJOPM-12-2019-0827

[61] Ghanbary, S., Salavatian, S., & Kia, A. (2020). Indicators of organizational resilience of iranian news agencies in natural disasters. *Emergency management*, *9*(1), 101–114. (**In Persian**). https://www.joem.ir/article_45871_01e9a0ccc84af65aabb4603886c5b5dd.pdf

[62] Khajepour, M., Farsijani, H., & Sedaghatparast, E. (2019). A model for organizational resilience in the banking industry. *Journal of strategic management studies*, *10*(37), 61–68. (**In Persian**). https://www.sid.ir/paper/181546/fa

[63] Coopmans, I., Bijttebier, J., Marchand, F., Mathijs, E., Messely, L., Rogge, E., … Wauters, E. (2021). COVID-19 impacts on Flemish food supply chains and lessons for agri-food system resilience. *Agricultural systems*, *190*, 103136. DOI:10.1016/j.agsy.2021.103136

[64] Rehak, D. (2020). Assessing and strengthening organisational resilience in a critical infrastructure system: case study of the Slovak Republic. *Safety science*, *123*, 104573. DOI:10.1016/j.ssci.2019.104573

[65] McManus, S., Seville, E., Vargo, J., & Brunsdon, D. (2008). Facilitated process for improving organizational resilience. *Natural hazards review*, *9*(2), 81–90. DOI:10.1061/(asce)1527-6988(2008)9:2(81)

[66] Shirali, G. A., Shekari, M., & Angali, K. A. (2016). Quantitative assessment of resilience safety culture using principal components analysis and numerical taxonomy: a case study in a petrochemical plant. *Journal of loss prevention in the process industries*, *40*, 277–284. DOI:10.1016/j.jlp.2016.01.007

[67] Wood, M. D., Wells, E. M., Rice, G., & Linkov, I. (2019). Quantifying and mapping resilience within large organizations. *Omega (United Kingdom)*, *87*, 117–126. DOI:10.1016/j.omega.2018.08.012

[68] Rahi, K. (2019). Indicators to assess organizational resilience – a review of empirical literature. *International journal of disaster resilience in the built environment*, *10*(2–3), 85–98. DOI:10.1108/IJDRBE-11-2018-0046

[69] Fasey, K. J., Sarkar, M., Wagstaff, C. R. D., & Johnston, J. (2021). Defining and characterizing organizational resilience in elite sport. *Psychology of sport and exercise*, *52*, 101834. DOI:10.1016/j.psychsport.2020.101834

[70] Rezaei Soufi, H., Esfahanipour, A., & Akbarpour Shirazi, M. (2021). Risk reduction through enhancing risk management by resilience. *International journal of disaster risk reduction*, *64*, 102497. DOI:10.1016/j.ijdrr.2021.102497

[71] Sapeciay, Z., Wilkinson, S., & Costello, S. B. (2017). Building organisational resilience for the construction industry: New Zealand practitioners' perspective. *International journal of disaster resilience in the built environment*, *8*(1), 98–108. DOI:10.1108/IJDRBE-05-2016-0020
[72] Mallak, L. A. (1998). Measuring resilience in health care provider organizations. *Health manpower management*, *24*(4–5), 148–152. DOI:10.1108/09552069810215755
[73] Sincorá, L. A., Oliveira, M. P. V. de, Zanquetto-Filho, H., & Ladeira, M. B. (2018). Business analytics leveraging resilience in organizational processes. *RAUSP management journal*, *53*(3), 385–403.
[74] Bertolozzi-Caredio, D., Garrido, A., Soriano, B., & Bardaji, I. (2021). Implications of alternative farm management patterns to promote resilience in extensive sheep farming. a Spanish case study. *Journal of rural studies*, *86*, 633–644. DOI:10.1016/j.jrurstud.2021.08.007
[75] Smith, M. K. S., Smit, I. P. J., Swemmer, L. K., Mokhatla, M. M., Freitag, S., Roux, D. J., & Dziba, L. (2021). Sustainability of protected areas: Vulnerabilities and opportunities as revealed by COVID-19 in a national park management agency. *Biological conservation*, *255*, 108985. DOI:10.1016/j.biocon.2021.108985
[76] Qi, H., Faisal, A., & Ka, X. (2021). Negotiating the impacts of policy interventions among tourism organizations: adaptation and sensemaking. *Journal of hospitality and tourism management*, *47*, 476–484.
[77] Lopez-Ridaura, S., Sanders, A., Barba-Escoto, L., Wiegel, J., Mayorga-Cortes, M., Gonzalez-Esquivel, C., … García-Barcena, T. S. (2021). Immediate impact of COVID-19 pandemic on farming systems in Central America and Mexico. *Agricultural systems*, *192*, 103178. DOI:10.1016/j.agsy.2021.103178
[78] Lopez-Ercilla, I., Espinosa-Romero, M. J., Fernandez Rivera-Melo, F. J., Fulton, S., Fernández, R., Torre, J., … Amador, I. (2021). The voice of Mexican small-scale fishers in times of COVID-19: impacts, responses, and digital divide. *Marine policy*, *131*, 104606. DOI:10.1016/j.marpol.2021.104606
[79] Akgün, A. E., & Keskin, H. (2014). Organisational resilience capacity and firm product innovativeness and performance. *International journal of production research*, *52*(23), 6918–6937.
[80] Pal, R., Torstensson, H., & Mattila, H. (2014). Antecedents of organizational resilience in economic crises - an empirical study of Swedish textile and clothing SMEs. *International journal of production economics*, *147*(PART B), 410–428. DOI:10.1016/j.ijpe.2013.02.031
[81] Zarali, M.R., Mehrara, A., & Bagherzadeh, M. R. (2020). Designing a model for managerial indicators of organizational resilience with the aim of improving human resource management in Tehran Municipality. *Journal of urban economics and management*, *8*(4), 117–135. (**In Persian**). https://www.magiran.com/paper/2222114
[82] Vakilzadeh, K., & Haase, A. (2021). The building blocks of organizational resilience: a review of the empirical literature. *Continuity & resilience review*, *3*(1), 1–21. DOI:10.1108/crr-04-2020-0002
[83] Mont, O., Curtis, S. K., & Voytenko Palgan, Y. (2021). Organisational response strategies to COVID-19 in the Sharing economy. *Sustainable production and consumption*, *28*, 52–70. DOI:10.1016/j.spc.2021.03.025
[84] Yoo, K. J., Kwon, S., Choi, Y., & Bishai, D. M. (2021). Systematic assessment of South Korea's capabilities to control COVID-19. *Health policy*, *125*(5), 568–576. DOI:10.1016/j.healthpol.2021.02.011
[85] Alonso, A. D., & Bressan, A. (2015). Resilience in the context of Italian micro and small wineries: an empirical study. *International journal of wine business research*, *27*(1), 40–60.
[86] Manyise, T., & Dentoni, D. (2021). Value chain partnerships and farmer entrepreneurship as balancing ecosystem services: implications for agri-food systems resilience. *Ecosystem services*, *49*, 101279. DOI:10.1016/j.ecoser.2021.101279
[87] Wilson, R. L. (2016). Organizational resilience as a human capital strategy for companies in bankruptcy. *Work*, *54*(2), 309–323. DOI:10.3233/WOR-162302
[88] Varajão, J., Fernandes, G., Amaral, A., & Gonçalves, A. M. (2021). Team resilience model: an empirical examination of information systems projects. *Reliability engineering and system safety*, *206*, 107303. DOI:10.1016/j.ress.2020.107303
[89] Hosseini Fard, S. M., Feizy, T., Geramipour, M., Hosseini Fard, S. M., Feizy, T., & Geramipour, M. (2021). Social capital as a strategy to achieve organizational resilience for small and medium enterprises: a grounded theory approach. *Social capital management*, *8*(2), 235–260. (**In Persian**). https://jscm.ut.ac.ir/article_80190.html
[90] Koronis, E., & Ponis, S. (2018). A strategic approach to crisis management and organizational resilience. *Journal of business strategy*, *39*(1), 32–42.

[91] Mahmoudi, D., Alizadeh, S. Sh., Rasoulzadeh, Y., & Asghari Jafarabadi, M. (2020). Prioritizing thirteen dimensions of organizational resilience in the face of crises and major incidents. *Iran occupational health*, *17*(1), 792–806. (**In Persian**). https://www.sid.ir/paper/527596/fa

[92] Parsons, M., Glavac, S., Hastings, P., Marshall, G., McGregor, J., McNeill, J., … Stayner, R. (2016). Top-down assessment of disaster resilience: a conceptual framework using coping and adaptive capacities. *International journal of disaster risk reduction*, *19*, 1–11. DOI:10.1016/j.ijdrr.2016.07.005

[93] Varmazyari, H., & Imani, B. (2017). Analyzing resilience of rural businesses in Malekan county. *Journal of entrepreneurship development*, *10*(1), 181–200. (**In Persian**). https://jed.ut.ac.ir/article_62327.html

[94] Valinejad, B., Ashraf Ganjouie, F., & Esmaili, M. R. (2020). Identifying components and indicators of organizational resilience in private sports clubs. *Iranian journal of public policy in management*, *11*(40), 15–27. (**In Persian**). https://www.sid.ir/paper/951489/en

[95] Corlett, J., & McConnachie, T. (2021). Delivering resilience training to pre-registration student nurses in partnership with a reservist military organisation: a qualitative study. *Nurse education today*, *97*, 104730. https://doi.org/10.1016/j.nedt.2020.104730

[96] Sommer, S. A., Howell, J. M., & Hadley, C. N. (2016). Keeping positive and building strength: the role of affect and team leadership in developing resilience during an organizational crisis. *Group and organization management*, *41*(2), 172–202. DOI:10.1177/1059601115578027

[97] Teo, W. L., Lee, M., & Lim, W. S. (2017). The relational activation of resilience model: how leadership activates resilience in an organizational crisis. *Journal of contingencies and crisis management*, *25*(3), 136–147. DOI:10.1111/1468-5973.12179.

[98] Melián-Alzola, L., Fernández-Monroy, M., & Hidalgo-Peñate, M. (2020). Hotels in contexts of uncertainty: measuring organisational resilience. *Tourism management perspectives*, *36*, 100747. DOI:10.1016/j.tmp.2020.100747

[99] Mousa, M., Abdelgaffar, H. A., Chaouali, W., & Aboramadan, M. (2020). Organizational learning, organizational resilience and the mediating role of multi-stakeholder networks: a study of Egyptian academics. *Journal of workplace learning*, *32*(3), 161–181. DOI:10.1108/JWL-05-2019-0057

[100] Wang, J., Cooke, F. L., & Huang, W. (2014). How resilient is the (future) workforce in China? a study of the banking sector and implications for human resource development. *Asia pacific journal of human resources*, *52*(2), 132–154. DOI:10.1111/1744-7941.12026

[101] Heydari, A., Ostadtaghizadeh, A., Ardalan, A., Ebadi, A., Mohammadfam, I., & Khorasani-Zavareh, D. (2022). Exploring the criteria and factors affecting firefighters' resilience: a qualitative study. *Chinese journal of traumatology - English edition*, *25*(2), 107–114. DOI:10.1016/j.cjtee.2021.06.001

[102] Hosseini, M. H., Ali-Ahmadi, A. R., Delavar, A., & Farhadinia, R. (2019). Developing and explaining a model for resilient organizations with an innovation approach in manufacturing companies (case study: Iran's textile industry). *Modiriat-e-farda*, *18*(58), 203–218. (**In Persian**). https://www.sid.ir/paper/525774/fa

[103] Romiani, Z. (2022). Prioritizing the dimensions of organizational resilience in the ccontext of the corona crisis (case study of Khorramabad hospitals). *Emergency management*, *10*, 105–114. (**In Persian**). https://www.joem.ir/article_246942.html?lang=en

[104] Agrawal, A. K., Arora, P. K., Nafees, M., Khan, S. A., & Kumar, H. (2021). Assessment of health infrastructure in tackling COVID-19: a case study of European and American scenario. *Materials today: proceedings*, *47*, 3716–3719. DOI:10.1016/j.matpr.2021.01.916

[105] Koronis, E., & Ponis, S. (2018). Better than before: the resilient organization in crisis mode. *Journal of business strategy*, *39*(1), 32–42. DOI:10.1108/JBS-10-2016-0124

[106] Chatterjee, S., Chakraborty, S., Fulk, H. K., & Sarker, S. (2021). Building a compassionate workplace using information technology: considerations for information systems research. *International journal of information management*, *56*, 102261. DOI:10.1016/j.ijinfomgt.2020.102261

[107] Fang, S., Prayag, G., Ozanne, L. K., & de Vries, H. (2020). Psychological capital, coping mechanisms and organizational resilience: Insights from the 2016 Kaikoura earthquake, New Zealand. *Tourism management perspectives*, *34*, 100637. DOI:10.1016/j.tmp.2020.100637

[108] Byers, O. M., Fitzpatrick, J. J., McDonald, P. E., & Nelson, G. C. (2021). Giving while grieving: Racism-related stress and psychological resilience in Black/African American registered nurses. *Nursing outlook*, *69*(6), 1039–1048. DOI:10.1016/j.outlook.2021.05.010

[109] Khosravi, S., Najafi, A., Mohammadi, N., & Marjani, M. (2019). The correlation between financial health and business continuity of banks with the mediation of organizational resilience. *Journal of health promotion management*, *8*(4). (**In Persian**). http://jhpm.ir/article-1-1081-fa.html

[110] Chitsazan, H., Davari, A., & Jalali, M. (2018). Assessing factors affecting small and medium enterprises' resilience capacity (a study of automotive suppliers). *Journal of entrepreneurship development*, *11*(3), 421–440. (**In Persian**). https://jed.ut.ac.ir/article_69776.html?lang=en

[111] Cuellar-Fernández, B., Fuertes-Callén, Y., & Serrano-Cinca, C. (2021). Survival of e-commerce entrepreneurs: the importance of brick-and-click and internationalization strategies. *Electronic commerce research and applications*, *46*, 101035. DOI:10.1016/j.elerap.2021.101035

[112] Baştuğ, S., & Yercan, F. (2021). An explanatory approach to assess resilience: an evaluation of competitive priorities for logistics organizations. *Transport policy*, *103*, 156–166. DOI:10.1016/j.tranpol.2021.01.016

[113] Duarte Alonso, A., Kok, S., & O'Brien, S. (2020). Brexit, the wine sector and organisational resilience: an exploratory study of Spanish Wineries. *Review of international business and strategy*, *30*(3), 301–322.

[114] Carvalho, A. O. de, Ribeiro, I., Cirani, C. B. S., & Cintra, R. F. (2016). Organizational resilience: a comparative study between innovative and non-innovative companies based on the financial performance analysis. *International journal of innovation*, *4*(1), 58–69. DOI:10.5585/iji.v4i1.73

[115] Dehdashti, Sh., Aslani, Z., & Afrashteh, A. (2019). Effect of creative atmosphere and knowledge management on organizational resilience in export companies. *Journal of international business administration*, *2*(2), 65–93. (**In Persian**). https://www.sid.ir/paper/400120/fa

[116] Costa, F. H. D. O., Da Silva, A. L., Pereira, C. R., Pereira, S. C. F., & Gómez Paredes, F. J. (2020). Achieving organisational resilience through inbound logistics effort. *British food journal*, *122*(2), 432–447.

[117] Choudhury, M. U. I., Emdad Haque, C., & Doberstein, B. (2021). Adaptive governance and community resilience to cyclones in coastal Bangladesh: addressing the problem of fit, social learning, and institutional collaboration. *Environmental science and policy*, *124*, 580–592.

[118] Cuartero, N., & Tur, A. M. (2021). Emotional intelligence, resilience and personality traits neuroticism and extraversion: predictive capacity in perceived academic efficacy. *Nurse education today*, *102*, 104933. DOI:10.1016/j.nedt.2021.104933

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How Metaheuristic Algorithms Can Help in Feature Selection for Alzheimer's Diagnosis

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Abstract

Feature selection is the process of picking the most effective feature among a considerable number of features in the dataset. However, choosing the best subset that gives a higher performance in classification is challenging. This study constructed and validated multiple metaheuristic algorithms to optimize Machine Learning (ML) models in diagnosing Alzheimer's. This study aims to classify Cognitively Normal (CN), Mild Cognitive Impairment (MCI), and Alzheimer's by selecting the best features. The features include Freesurfer features extracted from Magnetic Resonance Imaging (MRI) images and clinical data. We have used well-known ML algorithms for classifying, and after that, we used multiple metaheuristic methods for feature selection and optimizing the objective function of the classification. We considered the objective function a macro-average F1 score because of the imbalanced data. Our procedure not only reduces the irreverent features but also increases the classification performance. Results showed that metaheuristic algorithms could improve the performance of ML methods in diagnosing Alzheimer's by 20%. We found that classification performance can be significantly enhanced by using appropriate metaheuristic algorithms. Metaheuristic algorithms can help find the best features for medical classification problems, especially Alzheimer's.

Keywords: Metaheuristic algorithm, Alzheimer's disease, MRI, Machine learning, Feature selection, Data mining.

1 | Introduction

Nowadays, a considerable amount of data is generated daily, and data-related technologies are advancing rapidly to cope. Data Mining (DM) is one of the methods to conclude helpful information from this massive amount of data with the help of Machine Learning (ML), pattern recognition, algorithms, and statistics. ML algorithms employed in solving different problems [1] specially disease diagnosis. Alzheimer's Disease (AD) is one of the problems, with a large amount of data produced for diagnosing and treating it. The exact causes of AD are not yet clear. However, there are some risk factors with proven effects on the cognitive function of the brain such as White Matter (WM), Gray Matter (GM), and Cerebrospinal Fluid (CSF) CerebroSpinal Fluids (CSFs) [2]. These biomarkers can be found by examining different types of imaging modalities like Magnetic Resonance Imaging (MRI), Functional Magnetic Resonance Imaging (fMRI), Positron Emission Tomography (PET), etc. There are also other neuropsychology tests used to classify Alzheimer's such as Clinical Dementia

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Rating (CDR), Mini-Mental State Examinations (MMSE), and AD Assessment Scale Cognitive (ADAS-Cog) [3]. However, physicians still have difficulty predicting Alzheimer's because these biomarker variations are difficult to generalize. This is where DM and ML models, that are trained on multiple factors, can help in diagnosing Alzheimer's [4], [5]. Raw data from MRI scans need to be adjusted and preprossedsed to be used by before-mentioned models. Preprossessing data also helps with models accuracy [6]. One commonly used methods in data preprocessing is Feature Selection (FS) [6], which tries to select the smallest and most valuable features from data, leading to better classification performance. As well as performance, FS can speed up the decision-making process. The FS process is considered an NP-hard searching problem [7]. When there are n features, it will be a 2n subset of features that can be used, and when n is large, the computation cost increases. Therefore, for high-dimensional data, exhaustively generating all possible subsets becomes impractical and computationally intensive. Forward sequential, backward sequential, random, and heuristic searches are all examples of search strategies that can be used to improve the efficiency of the FS method. Recently, metaheuristic algorithms have been successfully applied to many FS methods [8]. As there is still a lot of work to do to find the main features of AD in this paper, we proposed a novel method for selecting the best features among many extracted from MRI images in combination with other health factors. Our proposed approach focuses on the choice of feature selection algorithm to overcome computation cost problems employimg metaheuristic methods. Also, classified AD into three different groups. The article is planned as follows. The next section discusses the literature review of other authors who have used DM and ML algorithms to analyze Alzheimer's. Section 3 describes the proposed technique used for feature extraction from MRI images and optimizing the result by metaheuristics. Section 4 discusses the experiments and evaluation results. Finally, Section 5 presents the paper summary and conclusions.

Table 1. Demographic details of OASIS-3 subjects.

	Male	Female
Number of subjects	487	611
Age	70.17 (42.5-91.7)	67.78 (43.2-95.6)
Right-handed	433	546

2 | Literature Review

Healthcare costs today are much higher due to technological advances and demographic changes. Planning and managing treatment resources and facilities is critical to controlling and reducing these costs and providing the desired services to patients [9]. Multiple criteria are needed to be managed in health care like infection control surveillance, diagnosis and treatment of various diseases, healthcare resource management, customer relationship management, healthcare administration, hospital management and public health.

Artificial Intelligence (AI) models played a successful role in health care issues, especially managing detection, determination, and disease prediction costs [10]. Hariri et al. [11] developed a model for diagnosis of hear failure using AI models to manage treatment costs. In all the AI models developed for disease classification, feature selection was the most challenging task. It involves selecting the most distinct and relevant subset of features from a large set of features to represent the dataset. In recent years we have seen studies on feature selection in medical imaging. For example, an ML model developed by Zhang et al. [5] combines AD baseline features from MRI images, hypometabolism, and CSF to classify AD vs CN. In the proposed model, they used a multiple-kernel support vector machine. Non-imaging biomarkers with CSF and clinical data were also used to develop and compare ML models to classify CN versus Mild Cognitive Impairment (MCI) [12]. More recently, Stamate et al. [13] compared three ML models to classify CN versus AD, which XGBoost claimed to be the best one that used blood metabolite data with clinical and cognitive data. Demir et al. [14] implemented a convolutional neural network to extract features from MRI images. Multiple methods have been proposed to solve the feature selection problem, such as random and greedy search, exhaustive search, etc. Most of these methods suffer significant complications and high computational costs.

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Metaheuristics provide practical solutions in a considerable amount of time, optimizing classification performance and overcoming the curse of dimensionality by alleviating the consumption of large functions such as computational resources, storage, etc. Bahmani et al. [15] employed improved Whale Optimization Algorithm (WOA) and for flow shop scheduling and vehicle routing and showed efficiency of improved WOA in converging to optimal solution and achieve better solution in comparison to the Genetic Algorithm (GA). Dirik [16] applied fuzzy GA to detection of counterfeit banknotes. Zhang et al. [17] fit GA to solve the appointment scheduling problem.

Therefore, metaheuristic algorithms as a solution received extra attention in classification. For example, Negahbani et al. [18] examined coronary artery disease and proposed an evolution based search algorithm with fuzzy c-means classifier. Al-Tashi et al. [19] used Grey Wolf Optimizer (GWO) to select the best features and used SVM as a classifier for diagnosing cardiovascular disease. Mafarja and Mirjalili [20] applied Simulated Annealing (SA) algorithm as a local search method to enhance the WOA to choose the optimal subset of features to develop classification accuracy on datasets from the UCI data repository [21].

Overall, studies are conducted extensively on various modalities for AD diagnosis, but still, researchers are facing difficulties with finding the best features. Therefore, an active feature selection algorithm is essential in identifying key features. Also, most of the research concentrated on 2 class classifications and did not consider the MCI phase, which is a more critical phase in AD diagnosis.

3 | Research Methodology

In this section, we will discuss the preprocessing methods and steps we did for the classification and optimization of the classification method by feature selection. In the first step, we compared well-known algorithms of ML; Adaboost, GradientBoost, XGBoost, Light GBM, and Gaussian Naive Bayes for our data classification with 192 features extracted from brain images. In the next step, we optimize the ML algorithm using metaheuristic algorithms for feature selection.

The data we have used is from the OASIS-3 dataset, a newly introduced dataset for AD. It was prepared across studies in Washington University Knight Alzheimer disease research center over 15 years. Demographic information about it is illustrated in *Table 1*. Participants in this study ranging from 42 to 95 years old including Cognitively Normal (CN) and different stages of cognitive decline adults. OASIS-3 dataset contains over 2000 MR sessions, including structural and functional sequences. Imaging data is accompanied by dementia, and APOE status, which is the strongest genetic risk factor for AD diagnosis suggested in multiple papers [22]–[24], and longitudinal clinical and cognitive outcomes.

Table 2. Features description.

Variable	Description
SubCortGrayVol	Subcortical GM volume
CortexVol	Total cortical GM volume
IntraCranialVol	ICV, intracranial volume
CorticalWhiteMatterVol	Total cortical WM volume
TotalGrayVol	Total GM volume
SupraTentorialVol	Supratentorial volume
lhCortexVol	Left hemisphere cortical GM volume
rhCortexVol	Right hemisphere cortical GM volume
lhCortical WM Vol	Left hemisphere cortical WM volume
rhCortical WM Vol	Right hemisphere cortical WM volume
APOE	Apolipoprotein E
MMSE	Mini-mental state examination

Table 3. CDR details of OASIS-3 subjects.

Categories	Max CDR=0	Max CDR=0.5	Max CDR=1	Max CDR>2
Min CDR=0	605	192	39	14
Min CDR=0.5	-	66	61	50
Min CDR>1	-	-	31	36
Total	605	258	131	100

3.1 | Preprocessing

In this study, we used features extracted from T1w MRI images. These images were processed through Freesurfer. FreeSurfer is an imaging tool and the most widely used software for analysing brain images. It is used for the depiction of the cortical surface between white and GM, segmentation of WM from the rest of the brain, skull stripping, and many other purposes. We have used the statistical output from the subcortical segmentation. We also considered APOE and MMSE values because they are important risk factors for AD diagnosis. Some of the features we have used are described in *Table 3*. Overall, there were 2047 records, and from that, we eliminated records with missing APOE or MMSE.

We have created three classes based on the provided CDR scores in which a CDR value equaling zero represents the non-existence of Alzheimer's, a CDR equaling 0.5 represents MCI subjects, and a CDR greater than 0.5 represents the presence of AD. Detailed information about CDR values is shown in *Table 2*. Some patients have multiple records because they had multiple visits; we didn't want to have any overlap between train and test dataset. To overcome this problem for each subject, we kept the records with the biggest CDR value indicating Alzheimer's or MCI. After these steps, the number of data became 1006 records and included 659 CN, 265 MCI, and 82 severe Alzheimer's (AD). It can be seen that data distribution is imbalanced. We split the data as 70% for training and 30% for testing.

The impact of class imbalance on classification performance is a major issue [25], [26]. In these studies, authors discussed the impact of im-balanced classification on accuracy using various examples and showed reporting classification accuracy for a severely imbalanced classification problem could be dangerously misleading. Ac-curacy is not considered a good evaluation measure as the majority class overwhelms the errors of the minority class. It is appropriate to use macro-averaging metrics over micro-averaging to avoid a dominance of majority classes [27]. In this work, we used macro average F1 score as the performance metric and the objective function for optimizing. F1 score is the variant most often used when learning from imbalanced data, which weights precision and recall equally [28]. After preprocessing the data for discrimination of CN, MCI and AD we used Adaboost [29], Gradient Boost [30], XGBoost [31], Light GBM, and Gaussian Naive Bayes [32] classifiers with all the extracted features.

Table 4. Metaheuristic algorithms performance.

Classifier	Default F1-MAVG	NSF	PSO F1-MAVG	NSF	GWO F1-MAVG	NSF	DFO F1-MAVG	NSF	GA F1-MAVG	NSF
AdaBoost	62.55%	198	78.04%	90	76.56%	181	77.00%	94	76.77%	198
Gradient boosting	78.09%	198	83.81%	96	82.40%	192	82.90%	112	83.13%	198
XGBoost	75.65%	198	85.13%	105	84.32%	189	83.60%	91	84.08%	198
LightGBM	75.14%	198	82.97%	89	82.80%	183	82.00%	102	82.37%	198
Gaussian naive bayes	52.92%	198	72.30%	87	67.72%	148	69.20%	87	66.29%	198

*Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO), Dragonfly Optimization (DFO), Genetic Algorithm (GA), F1 score Macro Average (F1 MAVG), Number of Selected Features (NSF).

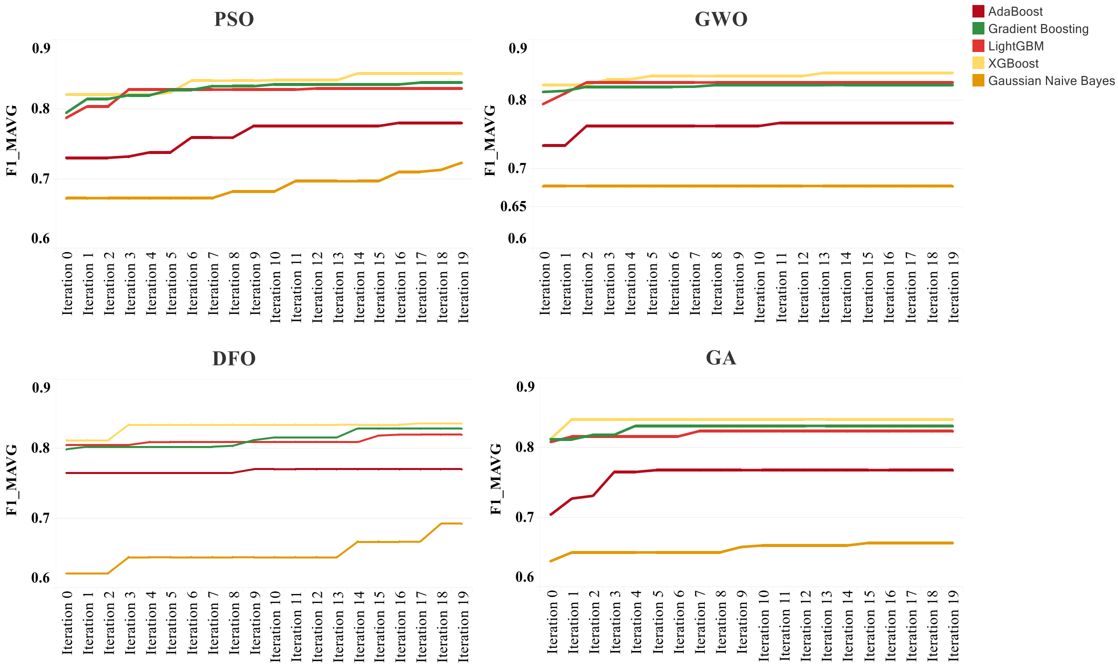

Fig. 1. Different meta-heuristic algorithms' performance on feature selection and different classifiers.

3.2 | Feature Selection

Feature selection has been considered to be an NP-hard problem [33] as it is a challenging problem to find the best subset of features. Therefore, more like other NP-hard problems, a high-performance metaheuristic method is required to reduce processing time. The proposed method in this study aims to compare and propose the best metaheuristic method to find the optimal combination of features. We used Particle Swarm Optimization (PSO), GWO, Dragonfly Optimization (DFO) Algorithm and GA as our metaheuristics algorithms because of their exploration and exploitation ability. PSO is a computational method that optimizes an objective function by iteratively improving candidate solutions with respect to a given quality measure. It takes a population of candidate solutions and solves the problem by moving these particles in the search space according to a simple formula via their positions and velocities. Each particle's motion is influenced by its best-known position locally. It also leads to the best-known position in the search space that is updated as better positions found by other particles. GWO mimics the natural gray wolf leadership hierarchy and hunting mechanisms. GWO implements and optimizes multiple steps: hunt, loot search, loot siege and loot attack. The DFO algorithm is derived from static and dynamic swarm behavior. These two herd behaviors are very similar to exploration and exploitation in the metaheuristic phase. Dragonflies form subflocks and fly in static flocks over different regions, which is the main purpose of the exploration phase. In static flocks, on the other hand, dragonflies fly in one direction in larger flocks. This is an advantage during the recovery phase. GA was inspired by the process of natural selection, which belongs to the larger class of Evolutionary Algorithms (EAs). GAs, which rely on biologically-inspired operators such as mutation, crossover, and selection, are widely used to generate high-quality solutions to optimization and search problems. We considered the objective function as macro average F1 score. For each algorithm, we have trained for 20 iterations to reach a maximum macro average F1 score in Alzheimer's classification.

OASIS-3 has been used in experiments that demonstrated the proposed approach produces a statistically significant compact set of features and improves the F1 score in classification. Results showed that PSO outperformed other methods in selecting several features and leads to improving classification metrics.

4 | Results and Discussion

In this research, multiple experiments are set up to analyze the performance of metaheuristic feature selection methods among different classifiers for diagnosing Alzheimer's. Five benchmark classifiers AdaBoost, Gradient Boosting, XGBoost, LightGBM, and Gaussian Naive bayes were applied in these experiments to evaluate the performance of feature selection methods. This section discusses the experimental results of different classifiers with PSO, GWO, DFO, and GA feature selection methods on the OASIS-3 dataset.

Table 4 outlines the Macro average F1 score obtained over different algorithms. The training process is also shown in *Fig. 1*. We performed multiple experiments comparing the effect of metaheuristic methods on optimizing the classifiers. Results show metaheuristics increase the macro average F1 score between 4.31% to 19.38%. We can remark that based on the selected features by different optimizers, the performance of the PSO with the XGBoost classifier outperforms other optimizers and classifiers because it reaches 85.13% macro average F1 score which is about 9.48% better than using XGBoost alone. This proves PSO optimized XGBoost classifier's future performance on the unseen data, and hence it can be used as a candidate method for Alzheimer's diagnosis.

5 | Conclusion

This paper tackles the optimization of classification methods for AD diagnosing problems. The ML classification methods are modified, and feature selection is applied in hybrid mode. Four metaheuristic methods are proposed besides ML methods and compared against the previous ones. To assess our proposed method, OASIS3 dataset is used. This dataset contains MRI images for people aged 42 to 95 years old. The dataset is highly imbalanced and finding a proper solution for AD classification in this dataset is difficult.

Evaluation is performed using appropriate measures (Macro-average F1 score) for imbalanced data and results compared. We found that the performance of classifiers can be improved significantly by using appropriate features, and metaheuristic algorithms can help to find the best features for medical classification problems. The proposed method can be improved by using other metaheuristics. Furthermore, other ML or deep learning algorithms can be applied to investigate the solutions. Finally, another way of future research could be to study the effect of hyperparameters values on performance.

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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.

References

[1] Mohammadi, S., Hemati, N., & Mohammadi, N. (2022). Speech recognition system based on machine learning in persian language. *Computational algorithms and numerical dimensions*, *1*(2), 72–83.

[2] Zimmermann, J., Perry, A., Breakspear, M., Schirner, M., Sachdev, P., Wen, W., … & Solodkin, A. (2018). Differentiation of Alzheimer's disease based on local and global parameters in personalized virtual brain models. *NeuroImage: clinical*, *19*, 240–251.

[3] Salmon, D. P., & Bondi, M. W. (2009). Neuropsychological assessment of dementia. *Annual review of psychology*, *60*, 257–282. https://doi.org/10.1146/annurev.psych.57.102904.190024

[4] Zhang, D., & Shen, D. (2012). Alzheimer's disease neuroimaging initiative. Multi-modal multi-task learning for joint prediction of multiple regression and classification variables in Alzheimer's disease. *NeuroImage*, *59*(2), 895–907. https://doi.org/10.1016/j.neuroimage.2011.09.069

[5] Zhang, D., Wang, Y., Zhou, L., Yuan, H., & Shen, D. (2011). Multimodal classification of Alzheimer's disease and mild cognitive impairment. *NeuroImage*, *55*(3), 856–867.

[6] Guyon, I., & Elisseeff, A. (2003). An introduction to variable and feature selection. *Journal of machine learning research*, *3*(Mar), 1157–1182. https://www.jmlr.org/papers/volume3/guyon03a/guyon03a.pdf?ref=driverlayer.com/web

[7] Faris, H., Al-Zoubi, A. M., Heidari, A. A., Aljarah, I., Mafarja, M., Hassonah, M. A., & Fujita, H. (2019). An intelligent system for spam detection and identification of the most relevant features based on evolutionary random weight networks. *Information fusion*, *48*, 67–83. DOI:https://doi.org/10.1016/j.inffus.2018.08.002

[8] Zelinka, I. (2015). A survey on evolutionary algorithms dynamics and its complexity-mutual relations, past, present and future. *Swarm and evolutionary computation*, *25*, 2–14. https://www.sciencedirect.com/science/article/pii/S2210650215000437

[9] Ala, A., & Chen, F. (2020). Alternative mathematical formulation and hybrid meta-heuristics for patient scheduling problem in health care clinics. *Neural computing and applications*, *32*, 8993–9008.

[10] Aminoshariae, A., Kulild, J., & Nagendrababu, V. (2021). Artificial intelligence in endodontics: current applications and future directions. *Journal of endodontics*, *47*(9), 1352–1357.

[11] Hariri, A. H., Bagheri, E., & Davoodi, S. M. R. (2022). Presenting a model for the diagnosis of heart failure using cumulative and deep learning algorithms: a case study of tehran heart center. *Big data and computing visions*, *2*(1), 18–30. https://www.bidacv.com/article_145116.html

[12] Hassan, S. A., & Khan, T. (2017). A machine learning model to predict the onset of alzheimer disease using potential cerebrospinal fluid (CSF) biomarkers. *International journal of advanced computer science and applications*, *8*(12). https://pdfs.semanticscholar.org/f8f0/87dde0db02dd5bdf1ddfef61ee39b793d8ce.pdf

[13] Stamate, D., Kim, M., Proitsi, P., Westwood, S., Baird, A., Nevado-Holgado, A., … & Legido-Quigley, C. (2019). A metabolite-based machine learning approach to diagnose Alzheimer-type dementia in blood: results from the european medical information framework for alzheimer disease biomarker discovery cohort. *Alzheimer's & dementia: translational research & clinical interventions*, *5*(1), 933–938.

[14] Gu, F., Ma, S., Wang, X., Zhao, J., Yu, Y., & Song, X. (2022). Evaluation of feature selection for Alzheimer's disease diagnosis. *Frontiers in aging neuroscience*, *14*, 924113. https://pubmed.ncbi.nlm.nih.gov/35813964/

[15] Bahmani, V., Adibi, M. A., & Mehdizadeh, E. (2023). Integration of two-stage assembly flow shop scheduling and vehicle routing using improved whale optimization algorithm. *Journal of applied research on industrial engineering*, *10*(1). https://doi.org/10.22105/jarie.2022.329251.1450

[16] Dirik, M. (2022). Detection of counterfeit banknotes using genetic fuzzy system. *Journal of fuzzy extension and applications*, *3*(4), 302–312. https://www.journal-fea.com/article_154622.html

[17] Zhang, J., Chung, H. S. H., & Lo, W. L. (2007). Clustering-based adaptive crossover and mutation probabilities for genetic algorithms. *IEEE transactions on evolutionary computation*, *11*(3), 326–335. DOI:10.1109/TEVC.2006.880727

[18] Negahbani, M., Joulazadeh, S., Marateb, H. R., & Mansourian, M. (2015). Coronary artery disease diagnosis using supervised fuzzy c-means with differential search algorithm-based generalized Minkowski metrics. *Archive of biomedical science and engineering*, *1*(1), 006-0014. https://www.peertechzpublications.org/articles/ABSE-1-102.php

[19] Al-Tashi, Q., Rais, H., & Jadid, S. (2019). Feature selection method based on grey wolf optimization for coronary artery disease classification. *Recent trends in data science and soft computing: proceedings of the 3rd international conference of reliable information and communication technology (IRICT 2018)* (pp. 257-266). Springer International Publishing. https://doi.org/10.1007/978-3-319-99007-1_25

[20] Mafarja, M. M., & Mirjalili, S. (2017). Hybrid whale optimization algorithm with simulated annealing for feature selection. *Neurocomputing*, *260*, 302–312.

[21] UCI. (2015). *UCI repository of machine learning databases*. https://archive.ics.uci.edu/

[22] Sperling, R. A., Aisen, P. S., Beckett, L. A., Bennett, D. A., Craft, S., Fagan, A. M., … & Phelps, C. H. (2011). Toward defining the preclinical stages of Alzheimer's disease: recommendations from the national institute on aging-Alzheimer's association workgroups on diagnostic guidelines for Alzheimer's disease. *Alzheimer's & dementia*, *7*(3), 280–292.

[23] Crous-Bou, M., Minguillón, C., Gramunt, N., & Molinuevo, J. L. (2017). Alzheimer's disease prevention: from risk factors to early intervention. *Alzheimer's research & therapy*, *9*(1), 71. https://doi.org/10.1186/s13195-017-0297-z

[24] Van Cauwenberghe, C., Van Broeckhoven, C., & Sleegers, K. (2016). The genetic landscape of Alzheimer disease: clinical implications and perspectives. *Genetics in medicine*, *18*(5), 421–430. https://doi.org/10.1038/gim.2015.117

[25] Chawla, N. V. (2010). Data mining for imbalanced datasets: an overview. In *Data mining and knowledge discovery handbook* (pp. 875-886). Springer, Boston, MA. https://doi.org/10.1007/978-0-387-09823-4_45

[26] Hossin, M., & Sulaiman, M. N. (2015). A review on evaluation metrics for data classification evaluations. *International journal of data mining & knowledge management process*, *5*(2), 1-11. https://www.academia.edu/download/37219940/5215ijdkp01.pdf

[27] Choeikiwong, T., & Vateekul, P. (2016). *Improve accuracy of defect severity categorization using semi-supervised approach on imbalanced data sets* [presentation]. Proceedings of the international multi conference of engineers and computer scientists (Vol. 1). https://www.iaeng.org/publication/IMECS2016/IMECS2016_pp434-438.pdf

[28] He, H., & Ma, Y. (2013). *Imbalanced learning: foundations, algorithms, and applications*. Wiley-IEEE Press. http://dx.doi.org/10.1002/9781118646106

[29] Freund, Y., & Schapire, R. E. (1996). *Experiments with a new boosting algorithm* [presentation]. Proceedings of the thirteenth international conference on international conference on machine learning (Vol. 96, pp. 148–156). https://dl.acm.org/doi/10.5555/3091696.3091715

[30] Friedman, J. H. (2001). Greedy function approximation: a gradient boosting machine. *The annals of statistics*, *29*(5), 1189–1232. https://doi.org/10.1214/aos/1013203451

[31] Chen, T., & Guestrin, C. (2016). *Xgboost: a scalable tree boosting system* [presentation]. Proceedings of the 22nd acm sigkdd international conference on knowledge discovery and data mining (pp. 785–794). https://dl.acm.org/doi/abs/10.1145/2939672.2939785

[32] Rish, I. (2001). *An empirical study of the naive bayes classifier* [presentation]. IJCAI 2001 workshop on empirical methods in artificial intelligence (Vol. 3, No. 22, pp. 41-46). https://www.researchgate.net/publication/228845263_An_Empirical_Study_of_the_Naive_Bayes_Classifier

[33] Pal, S. K., & Skowron, A. (1999). *Rough-fuzzy hybridization: a new trend in decision making*. Springer-Verlag. https://dl.acm.org/doi/abs/10.5555/553340

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