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Analyzing the impact of sustainability on the network design and planning decisions in a spare part supply chain: An empirical investigation

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Abstract

Economical, environmental, and social issues are significant challenges for industries and governments nowadays. The spare parts impose high inventory costs on the companies and require human resources, energy, and budget for the repair operations. These issues justify integrating repair, and inventory management decisions to reduce costs. Since the system is interacting with the environment, incorporating the sustainability dimensions with network design and planning decisions help managers to make more reliable decisions. We investigated the social and environmental dimensions to cover the sustainability dimensions of the spare part supply chain. These attributes contribute to industry-oriented properties in real-world problems. This paper investigates a multi-objective model to minimize costs while maximizing sustainability in a repairable spare part supply chain. Life cycle assessment (LCA) is utilized to assess social and environmental dimensions. Finally, the model is solved using NSGA-II with a priority-based encoding and decoding procedure. The findings shed light on contributing to formulating the spare part supply chain sustainability which integrates the network design and planning decisions resulting in more reliable outcomes.
Keywords: Supply chain, spare parts, sustainability, NSGA-II, inventory

1-Introduction

Maintenance costs compose 15-40 percent of total production costs to make spare parts management prominently vital for many industries (Hora, 1987). The repairable spare parts are the primary resources used in the repairing operations, which account for about 80% of all the spare parts' values (Driessen, 2018). The shortage of spare parts constitutes more than 80% of systems' downtime (Kosanoglu et al., 2018). Besides the importance of spare parts availability, it is necessary to consider the trade-off between the stock level and inventory costs (González-Varona et al., 2020). Therefore, the integration of various decision fields, such as inventory management, order assignment, and network design, helps managers make more comprehensive and reliable decisions. Especially for the specific spare parts, you have no time to wait for purchase (den Boer et al., 2020).

Spare parts in strategic industries are high-value inventories of millions of dollars (Schulze & Weckenborg, 2012). So, excessive inventory imposes incredible costs on the companies; however, shortages of spare parts do the same. Companies can take advantage of repairing the equipment instead of purchasing them. Still, there are many challenges in supplying spare parts such as long lead-time,

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shortage in warehouses, and expensive, and low-quality spare parts (Frandsen et al., 2020). Given the recent difficulties, uncertainty in demand of spare parts and the companies' mission for environmental, social, and economical considerations complicate the decision-making. Recognition and implementation of the best planning approaches can reduce lead times, shortages, stock levels of spare parts, and total costs (Turan et al., 2018). The review of the state of the art in the spare parts supply chain (SPSC) indicates that recent works focused on routine SPSCs that do not consider decisions related to order allocation, inventory management, and repair assignment simultaneously. Additionally, incorporating environmental and social considerations enable decision-makers to assess the impact of strategic and tactical planning decisions. Also, we found that most studies focused on sustainability including the environmental and social dimensions did not pay sufficient attention to spare part supply chains considering the industry-oriented attributes and other decisions. A sustainable SPSC is presented in this paper to bridge this gap, integrating the mentioned decisions through a multi-objective mathematical model. The model consists of network design decisions, inventory management in warehouses, and order assignment to suppliers for the repairable spare parts that follow base stock policies that aim to minimize costs and negative environmental and maximize social sustainability. Life cycle assessment is used to examine sustainability including environmental and social aspects. Also, a case study is selected to indicate the validity of the model that is solved by NSGA-II using a priority-based encoding and decoding procedure. The model also helps managers in industries to make the right decisions regarding buying or making decisions through repair and purchase analyses.

This paper is organized into these sections: First, a literature review of the related research is provided in section 2. Then, the problem is defined in section 3. Then, The model is provided in section 4. The solution method is presented in section 5. Computational results are presented in section 6 and sensitivity analyses are presented in section 7. Finally, the conclusion and future research opportunities are expressed in section 8.

2-Literature review

In this section, we review the sustainability and integration decisions regarding the spare part supply chain. Today, environmental, economical, and social concerns affect decisions in supply chains (Pauliuk et al., 2017). The green supply chain is a theoretical method to reduce the negative environmental effects of an SC (Batista et al., 2018; Jayaram & Avittathur, 2015). Reverse logistics refers to the recovery of products after consumption or loss in performance, causing unsafe conditions(Agrawal et al., 2015). The CLSC integrates forward and reverse flows (Carrasco-Gallego et al., 2012). Recent research such as (Fonseca, M. C., 2010; Finkbeiner, M. (2011); Gholamian, M. R., 2017; Fathollahi-Fard, A. M., 2018, and Frandsen, C. S., 2020) are examples from the literature investigating repairable spare parts supply chain. Gholamian and Heydari (2017) also integrate the inventory management model into a network design considering routing decisions. Shih (2001) published a paper on reverse logistics planning for appliances and electronics in Taiwan. They presented a model to optimize the network design. Facilities in this network include collection centers, warehouses, and disassembly centers. The objective function of the mathematical model is to maximize total profit. Aras et al. (2008) presented a mixed-integer linear model to determine collection centers' locations. The model results in the optimal price so that it maximizes total profit. Fonseca et al. (2010) designed an uncertain bi-objective model for reverse logistics. In the proposed network, collection and recycling centers exist. The model formulates a multi-product and multi-tier network. In this network, strategic and tactical decisions, are considered. The model includes minimizing costs and negative environmental effects. Zhao et al. (2012) investigated multiple items, orders, deliveries, and distribution centers. The ABC analysis method is used to optimize costs. Torabi and Sharafat (2013) considered the sustainability criteria in determining oil facilities' location involving crude oil terminals, oil refineries, and refinery storage. The multi-objective model of the oil supply chain deals with uncertainty. The model is validated using the Iran oil industry data. Aliakbar Hasani (2014) considered a novel model for a seven-tier reverse supply chain, including primary and secondary customers, collection and redistribution centers, recovery, recycling, and disposal. The paper presents a reverse supply chain network to maximize profit and demand responsiveness. A memetic algorithm based on NSGA-II is provided to find the optimal Pareto solutions. Koskela et al. (2014) considered an integrated closed-loop network design considering uncertainty in demand and product return. The stochastic model is used to determine the optimal locations of remanufacturing facilities, processing facilities, capacity levels, and forward and reverse flows. The objective function aims to minimize costs. Choudhary et al. (2015) examined a CLSC and proposed a model that focuses on reducing carbon dioxide. Facilities in this network include production, distribution, collection, recycling, and disassembly centers. The proposed model minimizes costs. Heuristic and meta-heuristic algorithms have been used to solve the model. Hatefi et al. (2015) developed a forward and reverse SC considering the uncertainty and facility disruption. The reverse logistics starts with collecting the product from the customer and continues with the inspection. After inspection, the products are divided into two categories: recyclable and non-recyclable. The proposed mixed-integer linear model minimizes costs. Rashidi Komijan et al. (2015) presented a mixed-integer linear programming model for a forward-reverse supply chain to minimize total costs. The network includes suppliers, manufacturers, distributors, and end-users in forward supply chain and collection centers, recovery centers, and disposal centers in reverse logistics. The model considers multiple products and various vehicles with different capacities to minimize total costs. Farrokh et al.(2016) developed a stochastic robust fuzzy programming model for a CLSC that minimizes total costs. In this model, two sources of uncertainty exist. The first one comes from the randomness of the parameters. The second source of uncertainty is called epistemic uncertainty. Possibilistic distribution helps deal with the latter one, but the first one is handled with scenarios. Kim et al. (2018) declared that uncertainty in demand affects production planning in reverse logistics, so it makes supply chain management essential. They presented a robust model to maximize the total profit that outperforms the deterministic one. Zarbakhshnia et al. (2019) presented a model for designing a green forward and supply chain. The design and planning decisions are discussed in this research. The mixed-integer multi-objective mathematical model formulates the multi-product network. The first objective function is to minimize costs, and the second one minimizes the released carbon dioxide. The third objective function minimizes the operational machines—finally, the e-constraint method is used to solve the multi-objective model. Doan et al. (2019) employed a fuzzy approach in an uncertain model for the electronics reverse SC that minimizes costs. Fathollahi-Fard et al. (2020) investigated water supply and wastewater collection network. Wastewater is collected from agricultural, urban, and industrial zones. They presented a stochastic multi-objective uncertain model based on a real-world case. The first objective minimizes costs; the second one minimizes environmental impacts. The last objective function maximizes social benefits. Babaveisi et al. (2022) considered the integration of the planning and forecasting models for a repairable spare part supply chain to prevent sub-optimality. This paper presents two mathematical models, including the planning and forecasting models using a Support Vector Machine (SVM). They used a piecewise linearization technique to determine the optimal number of intervals. The analyses show that demand estimation by piecewise method and integrating the decisions optimizes the cost, improves forecasting accuracy, and planning performance.

We conclude that most of the research on the spare part supply chain does not discuss the sustainability decisions comprehensively by considering the network design and planning decisions. In this paper, we contribute to the sustainability of an SPSC for repairable spare parts by presenting a model that considers inventory management. This paper also assumes the repair capacity, assignment of failed equipment according to repair expertise, and uncertainty in demand. Table 1 shows a comparison of this study with recent research. This paper presents a repairable spare parts supply chain model to incorporate inventory management and network design decisions while taking sustainability dimensions into account. Given the reviewed papers, the contributions of this paper are listed in the following:

- Developing a stochastic model for designing and planning a sustainable repairable SPSC;
- This paper implements the Life Cycle Assessment (LCA) technique to assess the sustainability aspects;
- To the best of our knowledge, no recent work regarding repairable spare parts has discussed inventory management and network design decisions simultaneously;
- Considering economic, environmental, and social objective functions help cover all the recent aspects that are not covered in other works;
- Repair capacity, cost, and capability for repairable spare parts are not considered in other research.

Table 1. Comparison of this study with recent research

Author	Year	Facilities								Decisions					Sustainability dimensions			Case study	Uncertainty	Objective function			
		Warehouse	collection	Recycling	Repair	Inspection	Disassembly	Distribution	Production	Inventory Management	Inventory planning	Supplier order assignment	Distribution	Location	Economical	Environmental	Social			Minimizing cost	Maximizing responsiveness	Maximizing sustainability	Maximizing profit
Shih	2001	*	*				*							*									*
Aras et al.	2008		*											*									*
Fonseca et al.	2010		*	*									*			*		*		*		*	
Torabi	2013	*							*					*				*	*	*			
Hasani	2014		*	*				*					*	*							*		*
Koskela	2014			*					*					*					*	*			
Choudhary et al.	2015		*	*			*	*	*					*						*			
Hatefi et al.	2015			*		*							*	*					*	*			
Rashidi et al.	2015		*	*			*						*	*						*			
Farrokh et al.	2016		*	*				*	*			*	*	*					*	*			
Zarbakhshnia et al.	2018	*		*			*		*				*	*		*				*		*	
Kim et al.	2018			*	*				*			*	*	*					*				*
Doan et al.	2019		*	*	*		*						*	*				*	*	*			
Fathollahi-Fard	2020		*	*					*				*			*	*	*	*	*		*	
Babaveisi et al.	2022				*					*	*	*						*	*	*			
Present paper	**2022**	*			*	*	*			*	*	*		*	*	*	*	*	*	*		*	

3-Problem description

3-1-Integrated forward-reverse SPSC

A general perspective for the proposed problem is given in figure 1. This study presents a forward and reverse spare part supply chain formulated as a mathematical model considering sustainability dimensions. The flow in this network starts from the end-users' locations where equipment is installed. Defective equipment is transferred to the inspection center to specify whether the equipment is repairable or not. In this way, unrepairable equipment heads to disassembly centers to extract usable spare parts while new equipment replaces the defective ones. All the repair centers use the company's resources, such as human resources, energy, budget, and materials for the repair operation. The usable spare parts in disassembly centers are used in repair centers while the unusable spare parts are disposed to raw material manufacturers.

Spare parts used in the equipment are of high-value and low-demand types that need high responsiveness. Therefore, companies must hold spare parts to meet demand, while holding costs for such inventories will be very high due to their high value. So, integrating the decisions regarding warehouses and repair centers can optimize inventory levels while satisfying demand. Central warehouses assign orders to suppliers according to their price, defect rate, and capacity.

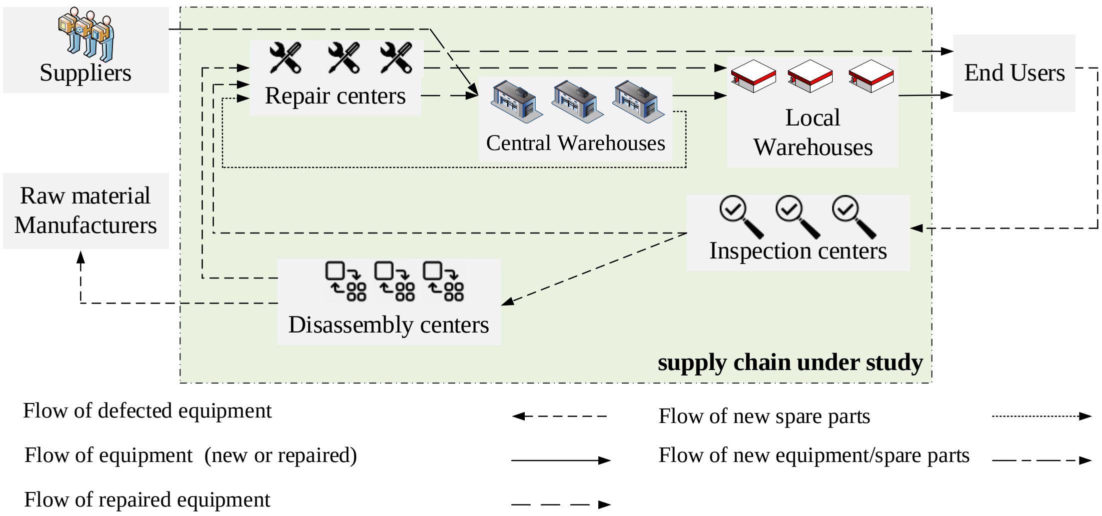

Fig 1. Proposed repairable spare part supply chain

Spare parts inventory management is a significant concern for decision-makers in industries and researchers. Expensive spare parts with low demand require the base stock (S-1, S) replenishment policy. We use the METRIC model to handle inventory management decisions such as order quantity, reorder point, and stock level in local and central warehouses. METRIC model is developed for repairable spare part inventory management which is the only model used in the context. The proposed mathematical model considers repair, network design, planning, and inventory management to make optimal decisions listed as follows:

- Determining stock level in central and local warehouses,
- Reorder point of spare parts in local and central warehouses,
- Order cycle and order quantity of central warehouses to suppliers,
- Flows between facilities in the supply chain,
- Location of repair centers, disassembly, and inspection centers,
- Inventory planning of spare parts in repair centers.

3-2-Sustainability dimensions

Life Cycle Assessment (LCA) is an approach to evaluate the consumption of resources and potential environmental effects throughout the products' whole life cycle. This technique considers manufacturing to end of life of services and products considering energy, material, ground, and water usage. In this way, the noticeable improvement is the fair use of resources and the avoidance of negative impacts in the supply chain.

Life Cycle Management (LCM) aims to improve services and products while enhancing sustainability measures. LCM was first discussed at Life Cycle Management Conference in 2001 (Jensen, 2001) and formally introduced by David Hunkeler (2004). It is extended by (Finkbeiner, 2011) afterward. LCM deals with the following ideas:

- Developing the scope to address both upstream and downstream parts of the SC,
- Applying economical, social, and environmental concepts throughout the whole life cycle,
- Connecting sustainability management with the organization's performance and value creation.

The triple bottom line (3BL) is a framework that incorporates economical, environmental, and social aspects. According to this concept, LCM links methods, tools, systems, policies, operational concepts, and data that integrate social, economic, and environmental considerations and their relations. The life cycle involves information that can be listed as the following:

- Communication with stakeholders and shareholders such as reports regarding sustainability and green accounting
- Communication with the public authorities
- Communication with the customers
- Communication with the public, wholesalers, and retailers

The PDCA[2] is a tool for quality management that improves sustainability performance. An essential outcome of sustainability is to ensure reducing energy and material resource consumption. We focus on sustainability dimensions, such as social, economical, and environmental aspects.

3-2-1-Economic dimension

Economic factors comprise a significant section of the decision-making process that affects other parts of the supply chain. The proposed model involves optimizing the facility location, stock level of warehouses, and order assignments directly connected with other supply chain decisions. The facilities' parameters include the opening costs of the warehouses, repair, inspection, and disassembly centers. The flows between facilities impose transportation costs. Also, the repairable equipment needs spare parts and other resources such as human resources, energy, and tools that include the purchase and holding cost, and tools in addition to human resource and energy costs. The rest of the equipment may impose disassembly costs and create salvage value. Additionally, the holding costs of the equipment and spare parts in central and local warehouses should be considered. Central warehouses assign orders to the suppliers that charge purchase costs to the company. The proposed model minimizes costs based on economic dimensions.

3-2-2- Environmental dimension

The LCA-based technique also considers the supply chain's environmental dimension associated with different product life cycle stages from supplying, distribution, repairing, and disassembly. Many works focused on transportation mode selection for spare parts logistic systems taking environmental issues into account (Digiesi et al., 2014). The environmental impacts are not only related to the transport operations, but also they concern the repairing and disassembly operations of the equipment. Also, repairing or purchasing the equipment has subsequent consequences that can be considered as possible impacts. Regarding the equipment transition, each vehicle consumes certain fuel per Kilometer and emits various pollutants; the prominent one being CO_2. Additionally, facility establishment causes

[2] Plan, Do, Check, and Act

negative environmental impacts. The mathematical model also minimizes environmental impacts such as pollutant emissions.

3-2-3- Social dimension

Social sustainability concerns improving the quality of human life that is assessed based on various criteria such as job opportunities, social welfare, and work injuries (Fathollahi-Fard & Hajiaghaei-Keshteli, 2018). In this study, we evaluate the establishment of the facilities to consider job opportunities and put repairing and disassembly operations under focus. Also, it is worth noting that the operational equipment continues working by replacing spare parts at the right time and holding the optimized stock level of spare parts. In this way, the product supply prevents chaos and increases social welfare. Job opportunities involve direct and indirect human resources in repair centers and disassembly centers. The social attributes are presented in table 2.

Table 2. Social attributes

Field of study	**Attributes**				
Human	Training	Job safety	Job hazard	Job opportunity	Insurance
Spare parts	Supply quality	Repair quality	Repair knowledge management		
Facilities	Paperwork				

4-Mathematical formulation

The sets, data, and decision variables of the developed mathematical model are presented in the following section.

4-1-Assumptions

- Central warehouses do not confront shortages at all,
- The demand of equipment (LRU[3]s) depends on spare parts (SRU[4]s),
- Each SRU exists only in one LRU,
- Base stock (S-1, S) replenishment policy is used for inventory management,
- Demands of spare parts during the lead time are stochastic and follow a Poisson distribution,
- Travel time between central and local warehouses is constant.

4-2-Indices and sets

$s \in S$	Spare part
$w \in W$	Warehouse
$w_1 \in W_1 \subseteq W$	Central warehouse (CW)
$w_2 \in W_2 \subseteq W$	Local warehouse (LW)
$r \in R$	Repair center (RC)
$i \in I$	Inspection center (IC)
$c \in C$	End-User
$d \in D$	Disassembly center (DC)
$m \in M$	Raw Material Manufacturer (RMM)
$s' \in S'$	Supplier

4-3-Parameters

$t_{ss'w_1}$	Travel cost of spare part s from supplier s' to CW w_1
$t_{sw_1w_2}$	Travel cost of spare part s from CW w_1 to LW w_2
t_{sw_2c}	Travel cost of spare part s from LW w_2 to end-user c
t_{srw}	Travel cost of spare part s from RC r to CW w_1
t_{src}	Travel cost of spare part s from RC r to end-user c

[3] Line-Replaceable Unit
[4] Shop-Replaceable Unit

t_{sdr}	Travel cost of spare part s from DC *d* to RC *r*
t_{sci}	Travel cost of spare part s from end-user *c* to IC *i*
t_{sir}	Travel cost of spare part s from IC *i* to RC *r*
t_{sid}	Travel cost of spare part s from IC *i* to DC *d*
t_{sdm}	Travel cost of spare part s from DC *d* to RMM *m*
$o_{ss'w_1}$	Ordering cost of spare part s for CW w_1 to the supplier s'
d_{sc}	The failure rate of spare part s for end-user *c*
f_r	Fixed establishment cost of RC *r*
f_i	Fixed establishment cost of IC *i*
f_d	Fixed establishment cost of DC *d*
f_w	Fixed establishment cost of warehouse *w*
rt_{sr}	The required work (Man-Hour) for repairing spare part s in RC *r*
cap_r	The capacity of RC *r*
cp_{rs}	1, if RC *r* can repair spare part *s*, 0 otherwise
$scap_{ss'}$	Capacity of supplier $s'$for spare part *s*
θ_{si}	Probability that LRU *s* at inspection center *i* is repairable
δ_{sd}	Probability that SRU *s* is usable in disassembly center *d*
$pr_{ss'}$	Purchase cost of spare part *s* for the supplier s'
$pu_{s_1s_2}$	Probability that spare part $s_1 \in s$ is used for repairing spare part $s_2 \in s$
$p_{s_1s_2}$	1, if spare part $s_1 \in s$ is a sub-component of spare part $s_2 \in s$, 0 otherwise
sv_s	Salvage value of each ton of defected spare part *s*
wt_s	Weight of each spare part *s*
h_{sw}	Holding cost of spare part s in warehouse *w*
$df_{ss'}$	Defect rate of spare part s from supplier s'
md_s	Maximum acceptable defect rate of spare part *s*
I_{sw}^0	Initial inventory of spare part *s* in warehouse *w*
I_{sr}^{r0}	Initial inventory of spare part *s* in RC *r*
$\tau_{sw_1w_2}$	Travel time of spare part *s* from CW w_1 to LW w_2
π_{sw}	Shortage cost of spare part *s* in warehouse *w*
$\mu_{ss'w_1}$	Leadtime of spare part *s* from supplier s' to CW w_1
$\tau_{sw_1} = \sum_{s'} \mu_{ss'w_1}$	Leadtime of spare part *s* supplied by CW w_1
hr_{sr}	Holding cost of spare part *s* in RC *r*
rc_{sr}	The repair cost of spare part *s* in RC *r*
dc_{sd}	Disassembly cost of spare part *s* in DC *d*
ndj_r	Direct job opportunities in repair center *r*
nij_r	Indirect job opportunities in repair center *r*
ndj_d	Direct job opportunities in the disassembly center *d*
nij_d	Indirect job opportunities in the disassembly center *d*
lw_r	The lost days of work during the establishment of repair center *r*
lw_d	The lost days of work during the establishment of the disassembly center *d*
ge_{rw}	Gas emission rate for traveling between repair center *r* and warehouse *w*
ge_{rc}	Gas emission rate for traveling between repair center *r* and end-user *c*
ge_{ir}	Gas emission rate for traveling between inspection center *i* and repair center *r*
ge_{id}	Gas emission rate for traveling between inspection center *i* and disassembly center *d*
ge_{dr}	Gas emission rate for traveling between disassembly center *d* and repair center *r*
$ge_{w_1w_2}$	Gas emission rate for traveling between the central warehouse w_1 and local warehouse w_2
ge_{ci}	Gas emission rate for traveling between end-user *c* and inspection *i*

4-4-Decision variables

$x^{(1)}_{ss'w_1}$	Number of spare part s from supplier s' to CW w_1
$x^{(2)}_{srw_1}$	Number of spare part s from RC *r* to CW w_1
$y^{(1)}_{sw_1w_2}$	Number of spare part s from the CW $w_1$to LW w_2
$y^{(2)}_{srw_2}$	Number of spare part s from RC *r* to LW w_2
$z^{(1)}_{sw_2c}$	Number of spare part s from LW $w_2$to end-user *c*
$z^{(2)}_{src}$	Number of spare part s from RC *r* to end-user *c*
x'_{sci}	Number of spare part s from end-user c to IC i
y'_{sir}	Number of spare part s from IC *i* to RC *r*
y''_{sid}	Number of spare part s from IC *i* to DC *d*
z'_{sdr}	Number of spare part s from DC *d* to RC *r*
z''_{sdm}	Number of spare part s from DC *d* to RMM *m*
w_{sw_1r}	Number of spare part s from CW w_1 to RC *r*
k_i	1, if IC *i* is opened, 0 else
k_r	1, if RC *r* is opened, 0 else
k_d	1, if DC *d* is opened, 0 else
k_w	1, if warehouse *w* is opened, 0 else
I^+_{sw}	The average on-hand inventory of spare part *s* in warehouse *w*
I^-_{sw}	The average shortage of spare part *s* in warehouse *w*
S_{sw}	Stock position of spare part *s* in warehouse *w*
sr_{sr}	Inventory level of spare part *s* at RC *r*
wa_{sw_1}	Average waiting time for replenishment spare part *s* in CW w_1
R_{sw}	Reorder level of spare part *s* at warehouse *w*
$Q_{ss'w_1}$	Order quantity of spare part *s* from the supplier s' for CW w_1
$D(\tau)$	Stochastic demand during lead time
λ_{sw}	Demand of spare part *s* in warehouse *w*

The inventory management model is formulated using METRIC. Demand during lead-time follows Poisson distribution and the mean of demand is as the following:

$$\lambda_{sw_1} = \sum_{w_2} Y^{(1)}_{sw_1w_2} \qquad \forall s, w_1 \qquad (1)$$

Expected on-hand inventory and shortage in warehouses for LRUs and SRUs are presented in equations (4), (7), and (8) (Wingerden et al., 2019).

$$I^+_{sw_1} = \sum_{j_s=1}^{s_{sw_1}} j_s \times (e^{-\lambda_{sw_1}\tau_{sw_1}}(\lambda_{sw_1}\tau_{sw_1})^{s_{sw_1}-j_s})/(s_{sw_1}-j_s)! \qquad (3)$$

$$\forall s(LRU), w_1$$

$$I_{sw_1} = I^+_{sw_1} - I^-_{sw_1}, I_{sw_1} = s_{sw_1} - \lambda_{sw_1}\tau_{sw_1}$$
$$I^-_{sw_1} = I^+_{sw_1} - (s_{sw_1} - \lambda_{sw_1}\tau_{sw_1}) \qquad (4)$$

Little law is presented in equation (5) to obtain the average waiting time for LRUs. The average lead time in local warehouses is presented in equation (6).

$$wa_{sw_1h} = \frac{I^-_{sw_1h}}{\lambda_{sw_1h}}, \lambda_{sw_1h} \neq 0 \qquad \forall s, w_1, h \qquad (5)$$

$$\bar{\tau}_{sw_2h} = \sum_{w_1, Y^{(1)}_{sw_1w_2h}>0} (\tau_{sw_1w_2} + wa_{sw_1h}) \qquad \forall s, w_2, h \qquad (6)$$

$$I^{+}_{sw_2h} = \sum_{j_s=1}^{s_{sw_2h}} j_s \times (e^{-\lambda_{sw_2h}\bar{\tau}_{sw_2}} (\lambda_{sw_2h}\bar{\tau}_{sw_2})^{s_{sw_2h}-j_s})/(s_{sw_2h} - j_s)! \qquad \forall s, w_2, h \qquad (7)$$

$$I_{sw_2h} = I^{+}_{sw_2h} - I^{-}_{sw_2h}, I_{sw_2h} = s_{sw_2h} - \lambda_{sw_2h}\tau_{sw_2}$$
$$I^{-}_{sw_2h} = I^{+}_{sw_2h} - (s_{sw_2h} - \lambda_{sw_2h}\bar{\tau}_{sw_2}) \qquad \forall s, w_2, h \qquad (8)$$

4-5-Objective function and constraints

$$Min\ z_{EC} = \left[\sum_{s}\sum_{s'}\sum_{w_1} t_{ss'w_1} x^{(1)}{}_{ss'w_1} \right. \qquad (9\text{-}1)$$

$$+ \sum_{s}\sum_{r}\sum_{w_1} t_{srw_1} x^{(2)}_{srw_1} + \sum_{s}\sum_{r}\sum_{w_2} t_{srw_2} y^{(2)}_{srw_2} + \sum_{s}\sum_{r}\sum_{c} t_{src} z^{(2)}_{src} \qquad (9\text{-}2)$$

$$+ \sum_{s}\sum_{w_1}\sum_{w_2} t_{sw_1w_2} y^{(1)}{}_{sw_1w_2} \qquad (9\text{-}3)$$

$$+ \sum_{s}\sum_{w_2}\sum_{c} t_{sw_2c} \times z^{(1)}_{sw_2c} \qquad (9\text{-}4)$$

$$+ \sum_{s}\sum_{c}\sum_{i} t_{sci} \times x'_{sci} \qquad (9\text{-}5)$$

$$+ \sum_{s}\sum_{i}\sum_{r} t_{sir} \times y'_{sir} + \sum_{s}\sum_{i}\sum_{d} t_{sid} \times y''_{sid} \qquad (9\text{-}6)$$

$$+ \sum_{s}\sum_{d}\sum_{r} t_{sdr}\, z'_{sdr} + \sum_{s}\sum_{d}\sum_{m} t_{sdm} \times z''_{sdm} \qquad (9\text{-}7)$$

$$+ \sum_{s}\sum_{r}\sum_{w_1} t_{srw_1} \times w_{sw_1r} \qquad (9\text{-}8)$$

$$+ \sum_{s}\sum_{w_1}\sum_{s'} o_{ss'w_1} \times (x^{(1)}{}_{ss'w_1}/Q_{ss'w_1}) \qquad (9\text{-}9)$$

$$+ \sum_{s}\sum_{s'}\sum_{w_1} pr_{ss'} \times x^{(1)}_{ss'w_1} \qquad (9\text{-}10)$$

$$+ \sum_{s}\sum_{w} h_{sw} I^{+}_{sw} \qquad (9\text{-}11)$$

$$+ \sum_{s}\sum_{r} hr_{sr} sr_{sr} \qquad (9\text{-}12)$$

$$+ \sum_{s}\sum_{w_2} \pi_{sw_2} I^{-}_{sw_2} \qquad (9\text{-}13)$$

$$+ \sum_{s}\sum_{i}\sum_{r} rc_{sr} y'_{sir} \qquad (9\text{-}14)$$

$$+ \sum_{s}\sum_{i}\sum_{d} dc_{sd} \times y''_{sid} \qquad (9\text{-}15)$$

$$+ \sum_{i} f_i\, k_i + \sum_{r} f_r\, k_r + \sum_{d} f_d\, k_d + \sum_{w} f_w\, k_w \qquad (9\text{-}16)$$

$$- \sum_{s}\sum_{d}\sum_{m} sv_s \times z''_{sdm} \qquad (9\text{-}17)$$

Equations (9-1) to (9-8) present the travel costs between facilities. Equation (9-9) calculates the ordering cost from suppliers, and equation (9-10) shows the purchase cost of equipment and spare parts ordered from suppliers. Equations (9-11) to (9-13) present the expected holding costs in warehouses, repair centers, and shortage costs in local warehouses. Repair and disassembly costs are expressed in equation (9-14) and (9-15). Facility fixed establishment costs are presented in (9-16). The last equation presents the total salvage costs. The objective function presented in (9-18) maximizes social sustainability. Each facility establishment provides direct and indirect job opportunities, although the construction of facilities makes job losses. Minimization of negative environmental impacts is shown in (9-19) which focuses on reducing gas emissions.

$$\text{Max } z_{SO} = \begin{bmatrix} g\left(\sum_{r}(ndj_r + nij_r)k_r + \sum_{d}(ndj_d + nij_d)k_d + \sum_{i} nj_i k_i\right) \\ -(1-g)\left(\sum_{r} lw_r k_r + \sum_{d} lw_d k_d + \sum_{i} lw_i k_i\right) \end{bmatrix} \tag{9-18}$$

$$\text{Min } z_{EN} = \begin{bmatrix} \sum_{s}\sum_{r}\sum_{w} ge_{rw} x^{(2)}_{srw} + \sum_{s}\sum_{r}\sum_{c} ge_{rc} z^{(2)}_{src} + \sum_{s}\sum_{i}\sum_{r} ge_{ir} y'_{sir} + \sum_{s}\sum_{i}\sum_{d} ge_{id} y''_{s} \\ + \sum_{s}\sum_{r}\sum_{d} ge_{dr} z'_{sdr} + \sum_{s}\sum_{w_1}\sum_{w_2} ge_{w_1 w_2} y^{(1)}_{sw_1 w_2} + \sum_{s}\sum_{c}\sum_{i} ge_{ci} x'_{sci} \end{bmatrix} \tag{9-19}$$

$$\sum_{r} z^{(2)}_{src} + \sum_{w_2} z^{(1)}_{sw_2 c} = d_{sc} \qquad \forall s, c \tag{10-1}$$

$$I^{+}_{sw_1} = \sum_{j_s=1}^{S_{sw_1}} j_s \times \left(e^{-\lambda_{sw_1}\tau_{sw_1}} (\lambda_{sw_1}\tau_{sw_1})^{S_{sw_1} - j_s}\right)/(S_{sw_1} - j_s)! \tag{10-2}$$

$$I^{-}_{sw_1} = I^{+}_{sw_1} - (S_{sw_1} - \lambda_{sw_1}\tau_{sw_1}) \qquad \forall s, w_1 \tag{10-3}$$

$$wa_{sw_1} = \frac{I^{-}_{sw_1}}{\lambda_{sw_1}}, \lambda_{sw_1} \neq 0 \tag{10-4}$$

$$\bar{\tau}_{sw_2} = \sum_{w_1, Y^{(1)}_{sw_1 w_2} > 0} (\tau_{sw_1 w_2} + wa_{sw_1}) \qquad \forall s, w_2 \tag{10-5}$$

$$I^{+}_{sw_2} = \sum_{j_s=1}^{S_{sw_2}} j_s \times \left(e^{-\lambda_{sw_2}\bar{\tau}_{sw_2}} (\lambda_{sw_2}\bar{\tau}_{sw_2})^{S_{sw_2} - j_s}\right)/(S_{sw_2} - j_s)! \qquad \forall s, w_2 \tag{10-6}$$

$$I^{-}_{sw_2} = I^{+}_{sw_2} - (S_{sw_2} - \lambda_{sw_2}\bar{\tau}_{sw_2}) \tag{10-7}$$

$$I^{0}_{sw_1} + \sum_{s'} x^{(1)}_{ss' w_1} + \sum_{r} x^{(2)}_{srw_1} = S_{sw_1} + \sum_{r} w_{sw_1 r} + \sum_{w_2} y^{(1)}_{sw_1 w_2} \qquad \forall s, w_1 \tag{10-8}$$

$$I^{0}_{sw_2} + \sum_{w_1} y^{(1)}_{sw_1 w_2} + \sum_{r} y^{(2)}_{srw_2} = S_{sw_2} + \sum_{c} z^{(1)}_{sw_2 c} \qquad \forall s, w_2 \tag{10-9}$$

$$\sum_{d} y''_{sid} = \sum_{c} (1 - \theta_{si}) \times x'_{sci} \qquad \forall s, i \tag{10-10}$$

$$\sum_{r} y'_{sir} = \sum_{c} \theta_{si} \times x'_{sci} \qquad \forall s, i \tag{10-11}$$

$$\sum_{i} y'_{sir} = \sum_{w_1} x^{(2)}_{srw_1} + \sum_{w_2} y^{(2)}_{srw_2} + \sum_{c} z^{(2)}_{src} \qquad \forall s, r \tag{10-12}$$

$$I^{r0}_{s_1 r} + \sum_{w_1} w_{s_1 w_1 r} + \sum_{d} z'_{s_1 dr} = pu_{s_1 s_2} \sum_{i} y'_{s_2 ir} + sr_{s_1 r} \qquad \forall s_1, s_2, r \tag{10-13}$$

$$\sum_{r} z'_{s_2 dr} = \sum_{i} \delta_{s_1 d} p_{s_1 s_2} y''_{s_2 id} \qquad \forall s_1, s_2, d \tag{10-14}$$

$$\sum_{m} z''_{s_2 dm} = \sum_{i} (1 - \delta_{s_1 d}) p_{s_1 s_2} y''_{s_2 id} \qquad \forall s_1, s_2, d \tag{10-15}$$

$$\sum_{w_1} x^{(1)}_{ss'w_1} \le scap_{ss'} \qquad \forall s, s' \qquad (10\text{-}16)$$

$$\sum_{i} x'_{sci} = d_{sc} \qquad \forall s, c \qquad (10\text{-}17)$$

$$\sum_{i} y'_{sir} \le M \times cp_{rs} \qquad \forall s, r \qquad (10\text{-}18)$$

$$\sum_{s}\sum_{i} rt_{sr} \times y'_{sir} \le cap_r \qquad \forall r \qquad (10\text{-}19)$$

$$\sum_{s'}\sum_{w_1} df_{ss'} x^{(1)}_{ss'w_1} / \sum_{w_1}\sum_{s'} x^{(1)}_{ss'w_1} \le md_s \qquad \forall s \qquad (10\text{-}20)$$

$$\sum_{w_1} x^{(1)}_{ss'w_1} \le M \times Z_{ss'} \qquad \forall s, s' \qquad (10\text{-}21)$$

$$\begin{array}{ll}
k_i \in \{0,1\} & \forall i \\
k_r \in \{0,1\} & \forall r \\
k_d \in \{0,1\} & \forall d \\
x'_{sci} \ge 0, int & \forall s, c, i \\
y'_{sir} \ge 0, int & \forall s, i, r \\
y''_{sid} \ge 0, int & \forall s, i, d \\
z'_{sdr} \ge 0, int & \forall s, d, r \\
z''_{sdm} \ge 0, int & \forall s, d, m \\
x^{(1)}_{ss'w_1} \ge 0, int & \forall s, s', w_1 \\
x^{(2)}_{srw_1} \ge 0, int & \forall s, r, w_1 \\
y^{(1)}_{sw_1w_2} \ge 0, int & \forall s, w_1, w_2 \\
y^{(2)}_{srw_2} \ge 0, int & \forall s, r, w_2 \\
z^{(1)}_{sw_2c} \ge 0, int & \forall s, w_2, c \\
z^{(2)}_{src} \ge 0, int & \forall s, r, c \\
S_{sw} \ge 0, int & \forall s, w \\
I^+_{sw}, I^-_{sw} \ge 0 & \forall s, w \\
Q_{ss'w_1} \ge 0, int & \forall s, s', w_1 \\
R_{sw_1} \ge 0, int & \forall s, w_1
\end{array} \qquad (10\text{-}22)$$

Constraint (10-1) ensures that the flow of spare parts to end-users satisfies demands. The METRIC model is presented in equations (10-2) to (10-7) that formulates the inventory management model of spare parts. Formulations for LRUs are presented in equations (10-2) and (10-6). Equation (10-3) and (10-7) respectively calculate the average on-hand and shortage inventory. Equation (10-8) expresses the balance of flows in central warehouses and equation (10-9) ensures the balance of input and output flows in local warehouses. The flows from inspection centers to disassembly centers and repair centers are calculated using equations (10-10) and (10-11). The balance of flows in repair centers is presented by equation (10-12). Each equipment requires some spare parts for the repairing operation; the balance of spare parts in repair centers is expressed in equation (10-13) which considers input and output flow, inventory level, and demand of spare parts repairing the equipment. Equations (10-14) and (10-15) determine the flow from disassembly centers to repair centers and raw material manufacturers. The constraint for the capacity of suppliers is presented in equation (10-16). Total reverse flow from an end-user should be equal to the demand that is expressed in equation (10-17). The assignment of equipment for repair is performed based on the repair expertise formulated as equation (10-18). Each repair center has a maximum repair capacity (Man-Hour) presented in (10-19). Moreover, suppliers will be qualified if the spare parts' defect does not exceed the allowed level, written as equation (10-20). The flow from the supplier to central warehouses is allowed if the supplier is selected, which is declared in equation (10-21). The domain of variables is presented in equation (10-22).

5-Solution method

The proposed model involves different decisions that increase the complexity. Also, the inventory management model increases the complexity; therefore, solving such a model by exact methods will be time-consuming or either be impossible even in small-size problems. To deal with the complexities, hybrid algorithms will be helpful to accelerate the solving process. In this paper, we use the genetic algorithm (GA) that is adapted to our problem by enhancing the encoding and decoding processes for the supply chain problem. First, the priority-based representation for the genetic algorithm is illustrated, then the mutation and crossover operators are presented. Finally, the encoding and decoding processes are specified in detail.

5-1-Chromosome representation

Encoding of the chromosomes is performed in three ways: 1) encoding according to the edge, 2) encoding according to vertex, and 3) encoding according to edge-vertex. The chromosomes contain the gene that holds two types of information including the so-called allele and locus. The locus illustrates the position of the gene i.e. the source or depot and the allele is the value. The highest priority in the chromosome is selected so that the locus specifies a vertex. In this paper, the representation is defined as a priority-based method that is tailored for the edge-vertex problems such as supply chain networks. The nodes are considered consecutive numbers whose priority will determine the edge connections. In each tier of the supply chain, the chromosome differs from another one. An example of the representation is shown in figure 2.

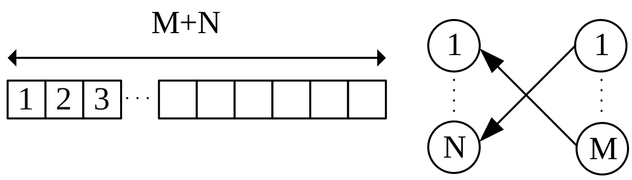

Fig 2. The priority-based representation

5-2-Operators

The mutation and crossover operators are defined in the following which helps generate new solutions. Since the priority-based chromosomes are used in this paper, mutation, and crossover should be defined so that they can prevent duplication; in this case, the order crossover (OX) is utilized. One or two cut points can be used to generate new offspring, shown in figure 3, which is created by selecting the parts of the parents. In the case of the mutation operator, two positions in the chromosome are selected randomly and the places are changed, shown in figure 4.

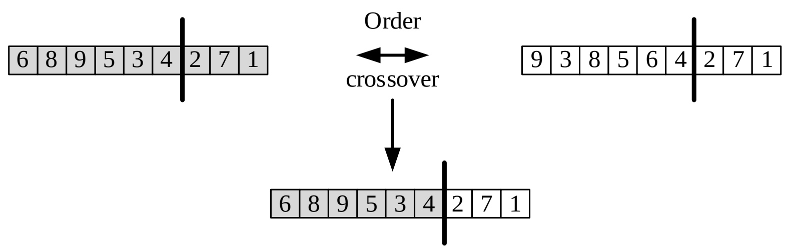

Fig 3. The order crossover

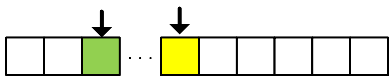

Fig 4. The mutation

5-3-Priority-based decoding

In previous sections, order-based representation was introduced. GA is a population-based algorithm that operates according to the solutions generated by chromosomes. According to priority-based decoding, a chromosome is decoded given the priority-based decoding algorithm that justifies the feasibility of the solutions. This algorithm works according to the priority of the genes i.e the allele. The search in the chromosome starts from the maximum priority value that specifies two nodes that should be connected through an edge. Figure 5 shows the results of a decoding procedure that is generated through this method. Sources and depots are limited by the capacity or demand which determines the amount of flow between the nodes. Transportation cost affects the connection between the sources and depots. The algorithm continues until all the capacity or demand is allocated considering the minimum value of capacity or demand at sources or depots. The pseudo-code for the priority-based algorithm is presented in the following.

Inputs:
S: Set of sources, D: set of depots,
tc: Transportation cost from sources to depots,
cap: **Capacity of** $\boldsymbol{sources}$,
$\boldsymbol{de}$: **Demand of** $\boldsymbol{depots}$
chromosome(**S*D**)
Outputs:
$\boldsymbol{X}$: **The flow between sources and depots**
$While \ \ all($**chromosome**$(:)) \neq 0$
  Step1.Chromosome generation: $ran \leftarrow argmax\{c\square(u), \mathrm{u} \in (|D| + |S|)\}$;
  Step2. Selecting node: $\boldsymbol{k}^* = \left\lceil \frac{\boldsymbol{ran}}{|\boldsymbol{D}|+|\boldsymbol{S}|)} \right\rceil$,
  Step3.determining sources and depots
    $v^* = argmin\{tc| \ \mathrm{ch} \neq 0,\}$, selecting a resource and depots with minimum transportation cost
  Step4. calculate the flow between the resource and depot
    $X = min\{\, cap, de\}$,
  Step5. Updating capacities
    $cap = cap - X, \ \ de = de - X$,
End

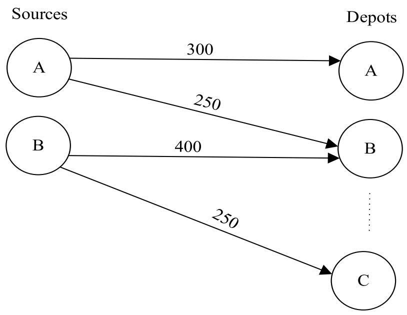

Fig 5. The Priority-based decoding

The multi-objective model in this research involves inconsistent objective functions such as minimizing costs and negative environmental effects and maximizing total sustainability. NSGA-II generates non-dominated points that are called Pareto solutions used to solve the model. NSGA-II is a Mehta-heuristic algorithm for solving multi-objective models. The populations are ranked by the non-dominated sorting method that creates the Pareto fronts. Also, the rank and the crowding distance are computed for each solution. The crowding distance equation (11) measures the expected distance of two close solutions. The boundary solutions with the lowest and highest objective function values take infinite crowding distance.

$$CD_i = (f_m^{i+1} - f_m^{i-1})/f_m^{max_m^{min}} \tag{11}$$

6-Computational results

In this section, data of the maintenance and repair operations of the National Iranian South Oilfields Company (NISOC) are used to pursue the validity of the model. The southern section of the territory is selected including Bushehr province to northern Khuzestan. The large oil fields in this territory, such as Ahwaz, Rag Sefid, Marun, Kranj, Gachsaran, Bibi Hakimeh, and, Aghajari are shown in figure 6.

Fig 6. The Southern territory of the National Iranian South Oilfields Company

Two central warehouses, three local warehouses, and five operational bases are considered in the supply chain. All the provinces include a local warehouse. Additionally, three inspection centers, three repair centers, and disassembly centers exist. The central warehouses are located in Ahwaz and Gachsaran. The distance between the repair centers and central warehouses is insignificant. The repairable equipment enters the repair centers while non-repairable equipment is disassembled in disassembly centers; destined for raw material manufacturers. The equipment and spare parts are presented in table 2.

Table 2. Equipment and spare parts

	Stator	**Burner**
1	joint	Panel pak filter
2	Filtometer	valve
3	switch	Washer
4	air filter	Swirler
5		Flame tube

The repair and disassembly operation involves certain costs that include human resources, tools, material, and energy costs that are presented in table 3. The maximum capacity of repair centers is 4000 Man-hours for repair operations which involves the working time of all the repair centers. The expected repair time is respectively 30 and 20 Man-hour for the burner and stator.

Table 3. Repair & disassembly costs

Equipment	**Repair center**	**Disassembly center**	**Repair time (Man-hour)**
Burner	300,000,000	30,000,000	30
Stator	350,000,000	20,000,000	20

Suppliers supply spare parts that differ in price, defect rate, and capacity which are presented in table 4. The maximum acceptable defect rate for equipment and spare parts is 0.05 and 0.1, respectively.

Table 4. Suppliers capacity, price, and defect rate

Code	Equipment/Spare parts	Supplier 1			Supplier 2			Supplier 3		
		Capacity	Price	Defect rate	Capacity	Price	Defect rate	Capacity	Price	Defect rate
1	**Burner**	**20**	**1160**	**0.01**	**20**	**1200**	**0.01**	**10**	**2000**	**0.01**
2	Flame tube	10	60	0.01	5	91.4	0.01	5	91.4	0.01
3	valve	50	30.51	0.05	20	30.13	0.05	20	30.20	0.05
4	Washer	500	0.34	0.01	500	0.45	0.01	500	0.5	0.01
5	Panel pak filter	100	3.03	0.1	50	3.20	0.1	50	3.00	0.1
6	Swirler	50	8.30	0.01	20	9	0.01	20	10	0.01
7	**Stator**	**10**	**3500**	**0.01**	**5**	**3000**	**0.01**	**5**	**4000**	**0.01**
8	joint	250	2	0.01	100	2.5	0.01	100	3	0.01
9	air filter	500	0.3	0.1	500	0.3	0.1	500	0.3	0.1
10	Filtometer	1000	1	0.02	500	2.0	0.01	500	2.1	0.02
11	Solenoid switch	500	0.2	0.1	100	0.17	0.1	300	0.22	0.1

It is supposed that the initial inventory in repair centers is zero. The inventory of central and local warehouses is shown in table 5. Demands of the operational bases are presented in table 6.

Table 5. Inventory level and holding cost

	Warehouses	Initial inventory											HCPU* (%)
		1	2	3	4	5	6	**7**	8	9	10	11	
Central warehouses	1	**1**	41	0	85	2	13	**18**	16	0	4	2	0.15
	2	**0**	0	10	0	0	0	**0**	0	0	0	0	0.15
Local warehouses	1	**0**	0	2	13	0	3	**0**	0	0	0	0	0.15
	2	**0**	0	0	15	0	0	**0**	3	0	0	0	0.15
	3	**0**	0	0	0	0	0	**0**	1	0	0	0	0.15
	4	**0**	0	0	0	0	0	**0**	2	0	0	0	0.15
	5	**0**	0	0	0	0	0	**0**	0	0	0	0	0.15

* Holding Cost Per Unit (%)

Table 6. Demands of operational bases

Equipment/ Spare parts	Operational bases				
	1	2	3	4	5
Burner	**3**	**0**	**1**	**0**	**2**
Panel pak filter	1	0	1	0	0
valve	1	0	0	0	1
Washer	1	0	0	0	0
Swirler	0	0	0	0	0
Flame tube	0	0	0	0	1
Stator	**1**	**1**	**0**	**0**	**1**
joint	0	0	0	0	0
Filtometer	0	1	0	0	0
switch	0	0	0	0	1
air filter	1	0	0	0	0

The probability of repairability is presented in table 7 which depends on the lifetime of equipment and spare parts, technical expertise, and company policies. Tables 8 and 9 show the usable spare parts in each equipment and salvage values, respectively. The probability of substituting or repairing the spare parts for each equipment can be seen in table 10.

Table 7. Probability of repairability

Equipment	Inspection centers		
	1	2	3
Burner	**0.8**	**0.8**	**0.8**
Stator	**0.5**	**0.5**	**0.5**

Table 8. Usable spare parts

Spare part	Disassembly centers		
	1	2	3
Panel pak filter	0	0	0
valve	1	1	1
Washer	0	0	0
Swirler	1	1	1
Flame tube	0	0	0
joint	1	1	1
Filtometer	1	1	1
switch	1	1	1
air filter	0	0	0

Table 9. Salvage value

Equipment/ Spare part	**Salvage value**
Burner	**116000000**
Panel pak filter	30300
valve	305100
Washer	3400
Swirler	83000
Flame tube	600000
Stator	**350000000**
joint	20000
Filtometer	10000
switch	2000
air filter	3000

Table 10. Probability of using spare part in an equipment

Spare parts	**Equipment**	
	Burner	Stator
Panel pak filter	0.20	-
valve	0.30	-
Washer	0.30	-
Swirler	0.10	-
Flame tube	0.10	-
joint	-	0.4
Filtometer	-	0.1
switch	-	0.4
air filter	-	0.1

We used the above data for the proposed model to show its validity. A PC with Intel Core i5 CPU @ 2.9 GHz and 16 GBs RAM is used to run the developed algorithm. The parameter patterns of the algorithm are illustrated in table 11 that are used for parameter tuning.

Table 11. Parameter tuning patterns

Parameter patterns	Population size	Crossover rate	Mutation rate	Iterations
P1	20	0.7	0.1	150
P2		0.5	0.3	
P3		0.3	0.5	
P4		0.1	0.7	
P5	30	0.7	0.1	
P6		0.5	0.3	
P7		0.3	0.5	
P8		0.1	0.7	
P9	50	0.7	0.1	
P10		0.5	0.3	
P11		0.3	0.5	
P12		0.1	0.7	

The Pareto points generated by NSGA-II are illustrated in figure 7 which shows the objective function values for each point. The results in table 12 show that the P9 pattern outperforms the others since its number of Pareto solutions (NPS) is greater than other patterns, so the decision-makers can opt for the different alternatives. Also, table 13 presents the value of the selected Pareto point.

Table 12. Number of Pareto solutions

Patterns	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
NPS	10	10	4	8	14	12	10	11	19	14	10	17

Table 13. Results of the selected Pareto point

Objective function	Z_{EC}	Z_{SO}	Z_{EN}
Value	4.42×10^9	98	9000

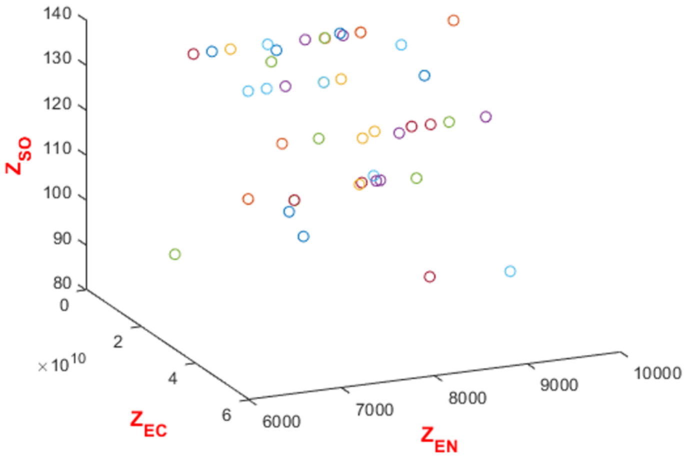

Fig 7. Pareto points generated by NSGA-II

The stock level of equipment and spare parts in warehouses are presented in table 14 which involves both central and local warehouses. It can be seen that the stock level of the equipment is low while the stock level of their spare parts is higher due to the higher amount of demand. Also, table 15 illustrates the results of order allocation to the suppliers.

Table 14. Stock levels in warehouses

	Warehouses	Stock levels										
		1	2	3	4	5	6	**7**	8	9	10	11
Central warehouses	1	**4**	38	1	84	2	12	**3**	16	0	4	0
	2	**2**	0	9	0	0	0	**0**	0	0	0	0
Local warehouses	1	**0**	0	1	13	0	3	**0**	0	0	0	0
	2	**0**	0	0	15	0	0	**0**	3	0	0	1
	3	**0**	0	0	0	0	0	**0**	1	0	0	0

Table 15. Supplier order assignment

Suppliers	**Equipment / Spare part**									
	1		**2**		**3**		**9**		**10**	
	Central warehouse									
	1	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
1	0	5	0	0	1	0	1	0	0	1
2	0	0	1	0	0	0	0	0	0	0

The repair allocation to repair centers is shown in table 16 based on the repair centers' capacity and capability. Non-repairable equipment is disassembled at disassembly centers, and destined for raw material manufacturers, shown in table 16. All of the defective equipment go to repair centers which means it is economical to repair the equipment instead of purchasing new branded ones.

Table 16. Equipment repair allocation

Inspection centers	**Equipment**	**Repair centers**		
		1	**2**	**3**
1	Burner	0	1	0
	Stator	0	1	1
2	Burner	0	3	0
	Stator	0	1	0
3	Burner	0	0	2
	Stator	0	0	0

7-Sensitivity analysis

We present sensitivity analyses in this section using the P9 parameter pattern problem. Stock level is a prominent variable since it directly affects the total cost. We examine the effects of fluctuation in shortage cost, holding cost, probability of repairability, and demand on stock level. The effect of fluctuations in demand on the stock level is illustrated in figure 8. It can be concluded that the stock level is dependent on demand so it increases when the demand increases and vice versa. The more the probability of repairability is, the less the stock level will be, as illustrated in figure 9. Also, it can be deduced that when the probability of repairability decreases, the stock level increases.

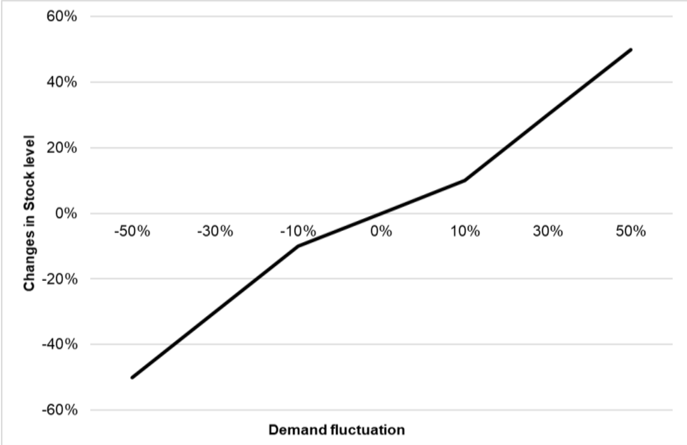

Fig 8. Changes in stock level vs. demand fluctuation

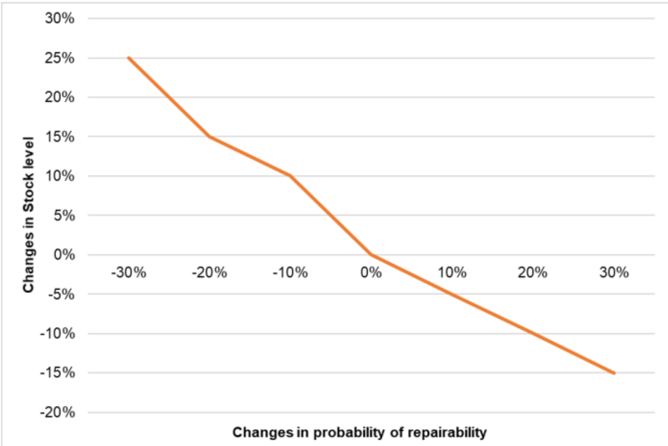

Fig 9. Fluctuation of the stock level vs. probability of repairability

Figure 10 shows the changes in stock level when backorder costs fluctuate. It can be seen that the stock level directly depends on the backorder cost which indicates an upward trend when the backorder cost increases and a downward trend in case the backorder cost decreases. The relation between stock level and holding cost is shown in figure 11 which indicates the decrease in stock level when the holding cost increases and vice versa.

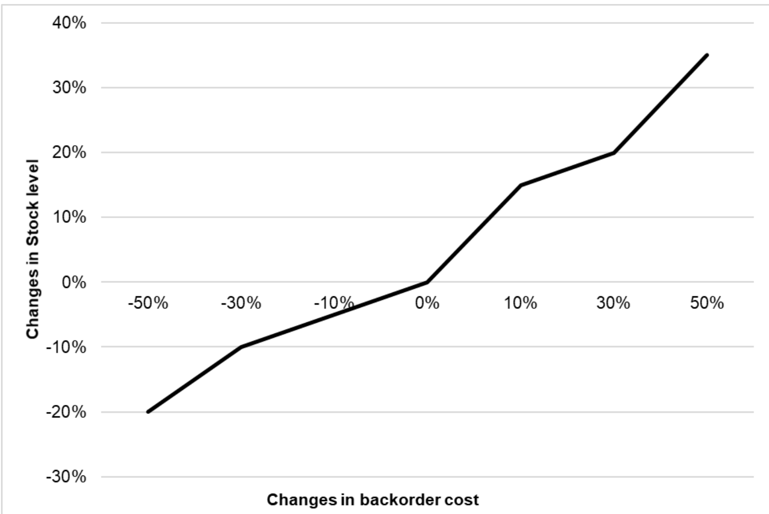

Fig 10. Changes in stock level when backorder cost changes

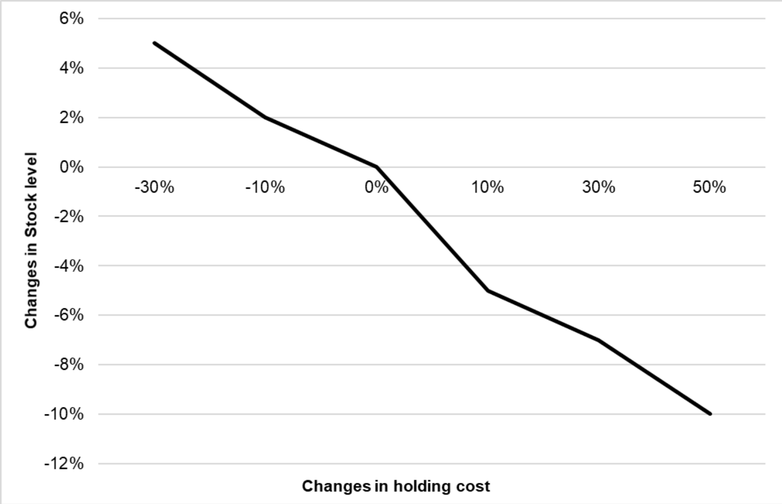

Fig 11. Changes in the stock level vs. changes in holding cost

Another important analysis regarding the fluctuation of the objective functions is shown in figure 12. It is shown that when the first objective function decreases, other objective functions increase. In other words, by increasing the objective function (obj2) of social sustainability and the objective function of environmental effects (obj3), total costs decrease which means more social sustainability can reduce costs, but negative environmental effects increase due to more facility establishment (i.e. it guarantees more jobs and spare part supply) and more transportation among the facilities.

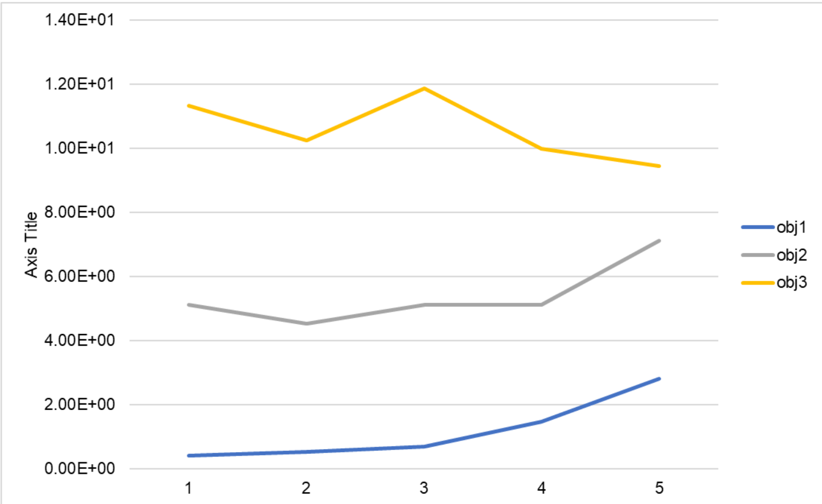

Fig 12. Fluctuation of the objective functions

8-Conclusion and future research opportunity

We considered a forward-reverse spare part supply chain to formulate a multi-objective model. This paper developed a sustainable forward-reverse repairable spare supply chain model to integrate life cycle assessment considering inventory management, network design, and planning. One of the purposes of the spare part supply chain design comes in enhancing the social and environmental aspects while optimizing the total costs. The model also considers the uncertainty in demand during the lead time, which makes the model more applicable. Due to the NP-hardness of the model, NSGA-II as a multi-objective meta-heuristic optimization approach is utilized that generates Pareto points. Data from the National Iranian South Oilfields Company is used in NSGA-II to solve the model. We also performed parameter tuning to obtain the best parameters for the algorithm. Finally, the results and the sensitivity analyses are presented that show the proper performance of the model and the algorithm. The results also bring some managerial insights: increasing social sustainability can reduce total costs while it may have negative impacts on the environmental effects. Also, we see that demand, holding cost, probability of the repairability, and backorder cost affect the stock level of the warehouses e.g. as the probability of the repairability increases, the stock level decreases since repairing the defective equipment can reduce the amount of equipment and spare parts that are needed to hold in warehouses. In this paper, we investigated the expensive equipment and spare parts with low demand in a single-period planning horizon. It would be precious if future researchers consider low and high-demand spare parts supply chain planning in multi-period problems. Also, other meta-heuristics can be investigated to examine their different performance.

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