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RESEARCH PAPER

A Forward-Reverse Repairable Spare Part Network Considering Inventory Management

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ABSTRACT

Production continuation highly depends on maintenance and repair operations that justify supporting the supply of spare parts for these purposes, especially in strategic industries. The integration of forward and reverse spare part logistics network can help optimize total costs. In this paper, a mathematical model is presented for designing and planning an integrated forward-reverse repairable spare parts supply chain (RSPSC) to make optimal decisions. The model considers the uncertainty in demand during the lead-time and the optimal assignment of repairable equipment. A METRIC (Multi-Echelon Technique for recoverable Item Control) model is integrated into the forward-reverse supply chain to handle inventory management decisions. A case study of the National Iranian Oil Company (NIOC) is presented to validate the model. The non-linear constraints are linearized by using a linearization technique; then the model is solved by an iterative procedure in GAMS. A prominent outcome of the analyses shows that the same policies for repair and purchase of all the equipment and spare parts do not result in optimal solutions. Also, considering all the supply, repair, and inventory management decisions help decision-makers enhance the supply chain's performance by applying well-balanced repairing and purchasing policies.

KEYWORDS: *Supply chain management; Network design; Inventory management; Logistics; Repairable spare part.*

1. Introduction

Reusing and recycling materials have a long history. These decisions increase the manufacturer's responsibility not only during production but also after production [1]–[5]. Forward and Reverse supply chains are essential parts of any business that must be implemented effectively throughout the economy. The closed-loop supply chain integrates the forward and reverse flow. These supply chains can be ranked similarly to forward supply chains to measure performance [6], [7].

Maintenance is an inseparable part of operations in industries which constitutes 15-40 percent of total production costs [8]. Maintenance and repair operations (MRO) require several resources, such as human resources, material, budget, and time. Spare parts are the essential materials used in MRO, which absorb major capital. As a tangible example, spare part inventory management costs include salaries, orders, and fixed costs (buildings and utilities), which add up to about %20 per year to purchase cost as inventory management costs can be generalized to other spare parts.

The essence of spare parts necessitates holding safe stuck in warehouses, which additionally consume storeroom, time, cost, and energy. Therefore, well-organized inventory management can save money to a significant degree of the extent [9]. Since companies' financial resources are limited, integrating forward and reverse spare part supply chain can reduce total costs through repairing, reusing, and remanufacturing [10].

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In this research, a mathematical model is presented for network design and planning of a forward-reverse repairable spare parts supply chain that considers strategic and tactical decisions. The decisions involve the flows between facilities, inventory planning of spare parts in repair centers, and order assignment to suppliers. The proposed model also integrates the forward and the reverse supply chain considering inventory management decisions in warehouses following a two-echelon model. Since repairable spare parts are discussed in this paper, METRIC model is the common framework used in the literature.

The paper involves the following sections: First, a literature review of the related researches is provided in section 2. Then, the problem is stated in section 3. The model formulation is presented in section 4. A detailed case study is presented in section 5. The results and sensitivity analyses are presented in sections 6 and 7. Finally, conclusions and future research opportunities are expressed in section 8.

2. Literature Review

In this section, we review the researches relating to the forward-reverse supply chain over the recent years to investigate the research gaps in the closed-loop supply chain regarding the possible inventory management, repair, and supply decisions for low-demand products. We focus on the spare part as its demand characteristics subordinate the recent field. Jayaraman et al. (1999) proposed a closed-loop logistics model for remanufacturing. In this network, there are facilities such as remanufacturing, distribution centers, and collection centers. The objective function of the proposed model is to minimize total costs [11]. Chung & Wee (2008) addressed saving resources due to the importance of environmental considerations. For this purpose, a network design of disassembly, inspection, repair, modern production, and recycling centers is considered. Inventory planning is also under focus in the proposed model [12]. These researches do not consider supply planning decisions.

Sasikumar et al. (2010) proposed a model for the multi-tier reverse logistics network for recycling. The nonlinear programming model maximizes total profit [13]. Vahdani et al., (2012) presented a model for minimizing cost in a supply chain including, remanufacturing, recycling, distribution, collection, and processing centers. M/M/c queuing model is considered in processing centers [14]. He & Hu (2015) investigated the emergency supply chain and presented a mathematical model. In this supply chain, depot, distribution, and rescue centers are considered. A queuing model is formulated for minimizing response time. M/M/1 queuing model is considered for each node. To solve the model, a genetic algorithm is used [15]. Choudhary et al. (2015) examined a closed-loop logistics network and proposed a model that focuses on reducing carbon dioxide. Facilities in this network include production, distribution, collection, recycling, and disassembly centers. The mixed-integer linear programming model aims to minimize total costs. Heuristic and meta-heuristic algorithms have been used to solve the model [18]. Sarrafha et al. (2015) proposed a bi-objective model for an integrated production-distribution supply chain that includes manufacturers, distribution centers, retailers, and customers. The multi-product, multi-period model minimizes the total cost of the supply chain and the lost sale amount. The multi-objective Particle Swarm Optimization Algorithm (MOPSO) solves the model [19]. None of these researches considered inventory management decisions such as ordering, storing, and other related decisions besides the other decisions.

Hatefi et al. presented an uncertain model for the forward and reverse logistics network considering facility disruption. The products are collected from the customer and moved to the inspection centers then they are divided into two types of recyclable and non-recyclable [16]. The model optimizes the total costs. Mirakhorli (2014) presented a fuzzy multi-objective model for a closed-loop logistics network. This paper considers the forward and reverse logistics and defines the facilities such as production, distribution, collection-inspection. Recyclable products are used, and the rest is disposed. The customer's demand and the amount of returned products are uncertain [17]. Zohal & Soleimani (2016) proposed a multi-objective mathematical model for a closed-loop supply chain that minimizes costs and amounts of released carbon dioxide and maximizes revenue. The supplier, manufacturer, distributor, collection centers, recycling, and disassembly centers are defined in this network. The ant colony optimization algorithm is used to solve the model, and its performance is compared with the exact approach [20]. Pedram et al. (2017b) proposed a mixed-integer linear programming model. The model considers the uncertainty in demand, returned products, and the quality of returned products. The scenario-based approach is used to deal with this uncertainty. The model aims to maximize profit and minimize negative environmental

effects [21]. These researches focus on different decisions, but procurement decisions such as lead-time and replenishment time are not examined. Different analyses on these decisions can be helpful in performance assessment especially when uncertainty comes to the light.

Ahmadi kurd et al. (2017) presented a robust optimization model in a reverse logistics network, including locating treatment plants, storages, deciding on establishing the canals, and optimal flows. The deterministic model determines the locations and allocation. Finally, the model is validated by analyzing the case study of Tehran province [22]. Yadollahinia et al. (2018) examined a forward-reverse supply chain and developed a linear multi-objective, multi-period, and multi-product linear model considering uncertainty. They used robust optimization to deal with the uncertainty [23]. Kim et al. (2018) declared that production planning is affected by customers' demand uncertainty and reverse logistics issues. They presented a robust model to maximize the total profit that outperforms the deterministic one [24]. Doan et al. employed a fuzzy approach to deal with uncertain parameters in a model for the electronics reverse supply chain. The model aims to minimize total costs [25].

Tosarkani & Amin (2019) proposed an optimization model for a forward-reverse supply chain under uncertainty. In this research, a closed-loop multi-tier supply chain network for the acidic battery is designed in uncertain conditions. Fuzzy and stochastic programming are integrated to maximize profit under different scenarios. Also, the environmental considerations of the supplier, factory, and recovery centers have been considered. The proposed model is solved using CPLEX solver [26]. Sadeghi et al. (2020) developed a closed-loop supply chain model in the automotive spare parts manufacturing industry. The multi-period, multi-product model aims to minimize total costs. This model covers facility location and routing decisions [27].

Table 1 shows the comparison of reviewed papers from the objective function, case study, decisions, uncertainty, and the structure of the supply chain. The research gap is presented in the following:

- This study discusses repairable equipment and spare parts that are inherently different from other products regarding low demands and expensive values
- Inventory management decisions are not considered with others such as supply and repair in reviewed works
- In other researches that discuss repair decisions, they did not focus on inventory planning and repair capability. Also, we consider the capacity of repair centers which make the model more realistic
- To the best of our knowledge, previous researches just focused on separate deterministic or stochastic models, but we consider an integrated model that can enhance the results; additionally, performance assessment is examined in this paper
- Papers that discussed stochastic demand, used a constant parameter for the mean value, but we consider it as a variable that makes the model more realistic.

3. Problem Statement

Industries impose high maintenance costs to ensure the proper performance of the equipment. Spare parts are a must in supporting the maintenance and repair operations in strategic industries. Therefore, companies hold essential spare parts to achieve high responsiveness in maintenance and repair operations, but holding the low-demand rate and expensive spare parts declines the liquidity. Thus, inventory management can reduce excess inventory and increase the liquidity while maintaining the service level. High inventory levels would be futile and it can impose huge costs on the companies. Since many years ago, companies have decided to deal with this problem in various industries through an integrated forward-reverse supply chain.

In this paper, we discuss the process of repairing the repairable spare parts and supplying the spare parts. The suppliers supply equipment and spare parts used in repairing the equipment. An equipment involves some spare parts that should be repaired or replaced when becomes defective. Integrating the supply and repair decisions leads to optimal decisions in all parts of the supply chain. The proposed supply chain is shown in Figure 1.

Defective equipment moves from end-users to inspection centers where repairable or non-repairable equipment is specified. Repairable equipment is assigned to the repair center according to capability, repair time, and capacity, and non-repairable equipment is disassembled in disassembly centers. Repair centers need spare parts for repairing equipment, supplied from disassembly centers or central warehouses. Unusable spare parts from non-repairable equipment in disassembly centers are destined to raw material manufacturers. New branded

equipment and spare parts are supplied from suppliers. A two-echelon inventory model, formulated using METRIC, is integrated into the forward-reverse supply chain, which handles inventory management decisions to minimize total costs. The integrated mathematical model makes optimal decisions as the following:

- Order assignment to suppliers considering purchase cost, defect rate, and the supplier capacity;
- Determining the optimal stock in central and local warehouses;
- Inventory planning in repair centers;
- Optimal assignment of equipment and spare parts to facilities.
- Average replenishment time in local warehouses;

4. Mathematical Formulation

In this section, first, the model's assumptions are described, then the indices, parameters, and decision variables are presented. Spare part as a unique terminology can mean equipment or spare part (sub-component of equipment)

4.1. Assumptions

- Repairable spare parts are discussed in this study;
- All the usable spare parts of the repairable equipment are stocked in repair centers;
- The locations of the facilities are predefined;
- Travel time between central and local warehouses is a constant;
- Demand rates of spare parts during the lead time are stochastic and follow a Poisson distribution;
- Each SRU is only found in one LRU;
- Replenishment policy in warehouses follows the base stock policy (s-1, s);
- Shortage never happens in central warehouses;
- Repair costs of spare parts involve human power, material, tools, and energy

Tab. 1. Comparison of present paper with the reviewed researches

		Facilities							Decisions						Objective function				
Author	year	Remanufacturing	collection	Recycling	Repair	Inspection	Disassembly	Distribution	Production	Inventory Management	Inventory planning	Supplier selection	Location	Case study	Minimizing cost	Maximizing sustainability	Maximizing profit	Minimizing response time	Uncertainty
Jayaraman et al.	1997	*	*					*					*		*				
Chung and Wee	2008	*		*	*	*					*				*				
Sasikumar et al.	2010		*											*			*		
Vahdani et al.	2012	*	*	*				*					*		*				*
He and Hu	2015							*										*	*
Mirakhorli	2014		*			*		*							*				*
Choudhary et al.	2015		*					*	*						*				
Sarrafha et al.	2015							*							*				
Zohal et al.	2016		*	*				*	*						*	*			
Pedram et al.	2016		*	*				*								*	*		*
Zhalechian et al.	2016		*					*	*		*		*	*		*	*		*
Ahmadi kurd et al.	2017		*					*					*	*	*				*
Yadollahinia et al.	2018		*	*				*	*				*	*			*		*
Tosarkani et al.	2019	*							*				*				*		*
Sadeghi et al.	2020	*	*				*	*				*		*	*				
Present paper	2021	*			*	*	*			*	*	*		*	*				*

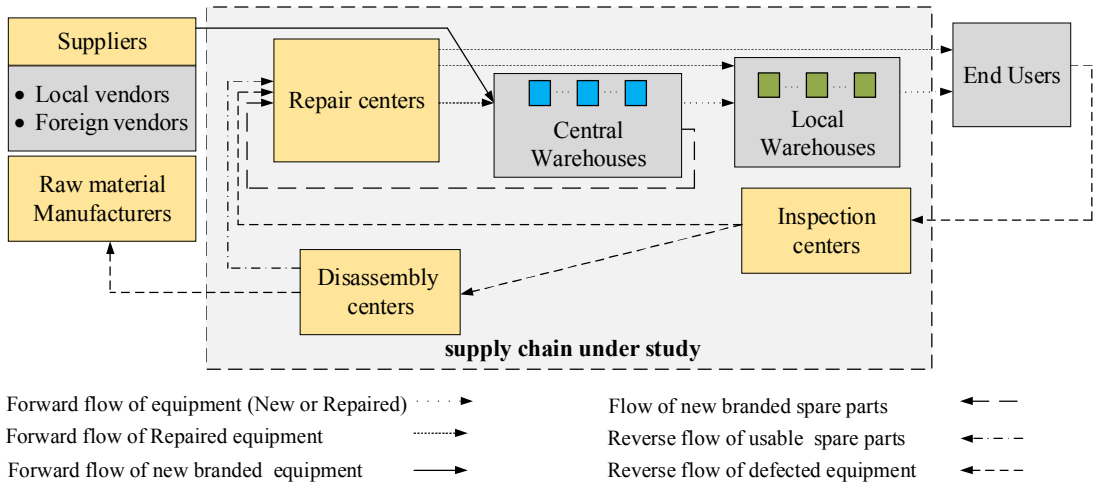


Fig. 1. The forward-reverse spare part supply chain

4.2. Indices and sets

$s, s_1, s_2 \in S$	Equipment and Spare parts
$w \in W$	Warehouses
$w_1 \in W_1 \ where\, W_1 \subseteq W$	Central warehouses
$w_2 \in W_2 \ where\, W_2 \subseteq W$	Local warehouses
$r \in R$	Repair centers
$i \in I$	Inspection centers
$c \in C$	End-users
$d \in D$	Disassembly centers
$m \in M$	Raw Material Manufacturers
$s' \in S'$	Suppliers
$s_1' \in S_1' \ where\, S_1' \subseteq S'$	Local Vendors
$s_2' \in S_2' \ where\, S_2' \subseteq S'$	Foreign vendors

4.3. Parameters

d_{sc}	Demand of end-user *c* from equipment/spare part *s*
$tc_{ss'w_1}$	Transportation cost of spare part *s* from supplier $s'$to central warehouse w_1
$tc_{sw_1w_2}$	Transportation cost of spare part s from central warehouse w_1 to local warehouse w_2
tc_{sw_2c}	Transportation cost of spare part s from warehouse w_2 to end-user *c*
tc_{srw}	Transportation cost of spare part *s* from repair center *r* to central warehouse *w*
tc_{src}	Transportation cost of spare part *s* from repair center *r* to end-user *c*
tc_{sdr}	Transportation cost of spare part *s* from disassembly center d to repair center r
tc_{sci}	Transportation cost of spare part *s* from end-user *c* to inspection center *i*
tc_{sir}	Transportation cost of spare part *s* from inspection center *i* to repair center *r*
tc_{sid}	Transportation cost of spare part *s* from inspection center *i* to disassembly center *d*

tc_{sdm}	Transportation cost of spare part *s* from disassembly center d to raw material manufacturer *m*
$A_{ss'w_1}$	Order cost of spare part *s* from central warehouse w_1 to supplier s'
rc_{sr}	The repair cost of spare part *s* in repair center *r*
rd_{sd}	The disassembly cost of equipment *s* in disassembly center d
rt_{sr}	The amount of work (Man-Hour) required for repairing spare part *s* in repair center *r*
cap_r	Available capacity (Man-Hour) in repair center *r*
cp_{rs}	1, if repair center *r* has the capability of repairing spare part *s*, 0 otherwise
$sc_{ss'}$	The capacity of supplier $s'$for spare part *s*
$pc_{ss'}$	Price of spare part s from supplier s'
$p_{s_1s_2}$	1, if $s_1 \in s$ is a sub-component of spare part $s_2 \in s$, 0 otherwise
sv_s	Average salvage value of unrepairable spare part *s*
h_{sw}	Holding cost of spare part s in warehouse *w*
hr_{sr}	Holding cost of spare part *s* in repair center *r*
$df_{ss'}$	Defect rate of spare part s from supplier s'
$pu_{s_1s_2}$	Probability of using spare part s_2 for repairing equipment s_1
md_s	Maximum acceptable defect rate of spare part *s*
I_{sw}^0	Initial inventory of spare parts s in warehouse *w*
$\tau_{sw_1w_2}$	Travel time of spare part *s* from central warehouse w_1 to local warehouse w_2
bc_{sw_2}	Backorder cost of spare part *s* in warehouse w_2
$\mu_{ss'w_1}$	Leadtime of spare part s from supplier s' to central warehouse w_1
α_{sd}	1, if spare part s in disassembly center *d* is usable, 0 otherwise
G_{si}	The proportion of repairability of equipment s in inspection center *i*
$\tau_{sw_1} = \sum_{s'} \mu_{ss'w_1}$	Leadtime of spare part *s* from central warehouse w_1

4.3. Decision variables

x'_{sci}	Amount of spare part *s* transfers from End User c to inspection center *i*
y'_{sir}	Amount of spare part *s* transfers from inspection center *i* to repair center *r*
y''_{sid}	Amount of spare part *s* transfers from repair center *i* to disassembly center *d*
z'_{sdr}	Amount of spare part *s* transfers from disassembly center d to repair center *r*
z''_{sdm}	Amount of spare part *s* transfers from disassembly center *d* to raw material manufacturer m
$x^{(1)}{}_{ss'w_1}$	Amount of spare part *s* transfers from supplier s' to the central warehouse w_1
$x^{(2)}{}_{srw_1}$	Amount of spare part *s* transfers from repair center r to the central warehouse w_1
$y^{(1)}{}_{sw_1w_2}$	Amount of spare part *s* transfers from the central warehouse $w_1$to the local warehouse w_2
$y^{(2)}{}_{srw_2}$	Amount of spare part *s* transfers from repair center *r* to the local warehouse w_2
$z^{(1)}{}_{sw_2c}$	Amount of spare part *s* transfers from local warehouse w_2 to End User *c*
$z^{(2)}{}_{src}$	Amount of spare part *s* transfers from repair center *r* to End User *c*

w_{sw_1r}	Amount of spare part *s* transfers from warehouse center w_1 to repair center *r*
I_{sw}	Expected inventory of spare part *s* in warehouse *w*
I_{sw}^{+}	Expected on-hand inventory of spare part *s* in warehouse *w*
I_{sw}^{-}	Expected shortage of spare part *s* in warehouse *w*
S_{sw}^{0}	Stock position of spare part *s* in warehouse *w*
sr_{sr}	Stock level of spare part *s* in repair center *r*
wa_{sw_1}	Average waiting time of replenishment spare part *s* in the central warehouse w_1
$\bar{\tau}_{sw_2}$	Expected lead-time time for spare part *s* in the local warehouse w_2
$D(\tau)$	Stochastic demand during lead time
λ_{sw}	Demand of spare part *s* in warehouse *w*

The two-echelon model formulates the inventory management system using METRIC. Each spare part is substituted based on the stock replenishment policy. The demand of each spare part in each warehouse during lead-time follows Poisson distribution and the mean of demand is as the following:

$$\lambda_{sw_1} = \sum_{w_2} y_{sw_1w_2}^{(1)} \tag{1}$$

Average on-hand inventory and shortage in central and local warehouses are computed in (2,3) and (5-7) [28]. It is worth pointing out that the average shortage is computed for the central warehouse.

$$I_{sw_1}^{+} = \sum_{j_s=1}^{S_{sw_1}^{0}} j_s \times \frac{e^{-\lambda_{sw_1}\tau_{sw_1}}(\lambda_{sw_1}\tau_{sw_1})^{S_{sw_1}^{0}-j_s}}{(S_{sw_1}^{0}-j_s)!} \qquad \forall s, w_1 \tag{2}$$

$$\begin{aligned} I_{sw_1} &= I_{sw_1}^{+} - I_{sw_1}^{-}, \\ I_{sw_1} &= S_{sw_1}^{0} - \lambda_{sw_1}\tau_{sw_1} \\ I_{sw_1}^{-} &= I_{sw_1}^{+} - (S_{sw_1}^{0} - \lambda_{sw_1}\tau_{sw_1}) \end{aligned} \qquad \forall s, w_1 \tag{3}$$

Little law is presented in (4) to obtain the average waiting time.

$$wa_{sw_1} = \frac{I_{sw_1}^{-}}{\lambda_{sw_1}}, \lambda_{sw_1} \neq 0 \qquad \forall s, w_1 \tag{4}$$

$$\bar{\tau}_{sw_2} = \sum_{w_1, Y_{sw_1w_2}^{(1)}>0} (\tau_{sw_1w_2} + wa_{sw_1}) \qquad \forall s, w_2 \tag{5}$$

$$I_{sw_2}^{+} = \sum_{j_s=1}^{S_{sw_2}^{0}} j_s \times \frac{e^{-\lambda_{sw_2}\bar{\tau}_{sw_2}}(\lambda_{sw_2}\bar{\tau}_{sw_2})^{S_{sw_2}^{0}-j_s}}{(S_{sw_2}^{0}-j_s)!} \qquad \forall s, w_2 \tag{6}$$

$$\begin{aligned} I_{sw_2} &= I_{sw_2}^{+} - I_{sw_2}^{-}, I_{sw_2} = S_{sw_2}^{0} - \lambda_{sw_2}\tau_{sw_2} \\ I_{sw_2}^{-} &= I_{sw_2}^{+} - (S_{sw_2}^{0} - \lambda_{sw_2}\bar{\tau}_{sw_2}) \end{aligned} \qquad \forall s, w_2 \tag{7}$$

4.4. Objective function and constraints

$$Min\ Z = \left[\sum_{s}\sum_{s'}\sum_{w_1} tc_{ss'w_1} \times x^{(1)}{}_{ss'w_1}\right. \tag{8-1}$$

$$\begin{aligned} &+ \sum_{s}\sum_{r}\sum_{w_1} tc_{srw_1} \times x^{(2)}{}_{srw_1} \\ &+ \sum_{s}\sum_{r}\sum_{w_2} tc_{srw_2} \times y^{(2)}{}_{srw_2} \\ &+ \sum_{s}\sum_{r}\sum_{c} tc_{src} \times z_{src}^{(2)} \end{aligned} \tag{8-2}$$

$$+\sum_{s}\sum_{w_1}\sum_{w_2} tc_{sw_1w_2} \times y^{(1)}{}_{sw_1w_2} \tag{8-3}$$

$$+\sum_{s}\sum_{w_2}\sum_{c} tc_{sw_2c} \times z^{(1)}_{sw_2c} \tag{8-4}$$

$$+\sum_{s}\sum_{c}\sum_{i} tc_{sci} \times x'_{sci} \tag{8-5}$$

$$+\sum_{s}\sum_{i}\sum_{r} tc_{sir} \times y'_{sir} + \sum_{s}\sum_{i}\sum_{d} tc_{sid} \times y''_{sid} \tag{8-6}$$

$$+\sum_{s}\sum_{d}\sum_{r} tc_{sdr}\, z'_{sdr} + \sum_{s}\sum_{d}\sum_{m} tc_{sdm} \times z''_{sdm} \tag{8-7}$$

$$+\sum_{s}\sum_{w_1}\sum_{s'} A_{ss'w_1} \times x^{(1)}{}_{ss'w_1} \tag{8-8}$$

$$+\sum_{s}\sum_{s'}\sum_{w_1} pc_{ss'} \times x^{(1)}{}_{ss'w_1} \tag{8-9}$$

$$+\sum_{s}\sum_{w} \square_{sw} I^{+}_{sw} \tag{8-10}$$

$$+\sum_{s}\sum_{r} \square r_{sr} \times sr_{sr} \tag{8-11}$$

$$+\sum_{s}\sum_{w_2} bc_{sw_2} I^{-}_{sw_2} \tag{8-12}$$

$$+\sum_{s}\sum_{i}\sum_{r} rc_{sr} \times y'_{sir} \tag{8-13}$$

$$+\sum_{s}\sum_{i}\sum_{d} rd_{sd} \times y''_{sid}\Bigg] \tag{8-14}$$

$$-\sum_{s}\sum_{d}\sum_{m} sv_s \times z''_{sdm} \tag{8-15}$$

Terms (8-1) through (8-7) present the transportation costs between facilities. Ordering cost is expressed in Term (8-8). Term (8-9) shows the purchase cost of spare parts and equipment from suppliers. Term (8-10) and (8-11) show the holding costs in warehouses and repair centers. Term (8-12) represents the shortage costs in the local warehouse. Term (8-13) and (8-14) computes the repair and disassembly costs. Term (8-15) is the salvage value.

$$\sum_{w_2} z^{(1)}{}_{sw_2c} + \sum_{r} z^{(2)}{}_{src} = d_{sc} \qquad \forall s, c \tag{9}$$

$$\lambda_{sw_1} = \sum_{w_2} y^{(1)}_{sw_1w_2} \qquad \forall s, w_1 \tag{10}$$

$$\lambda_{sw_2} = \sum_{w_1} y^{(1)}_{sw_1w_2} \qquad \forall s, w_2 \tag{11}$$

$$I^{+}_{sw_1} = \sum_{j_s=1}^{S^0_{sw_1}} j_s \times \frac{e^{-\lambda_{sw_1}\tau_{sw_1}} (\lambda_{sw_1}\tau_{sw_1})^{S^0_{sw_1}-j_s}}{(S^0_{sw_1}-j_s)!} \qquad \forall s, w_1 \tag{12}$$

$$I^{-}_{sw_1} = I^{+}_{sw_1} - (S^0_{sw_1} - \lambda_{sw_1}\tau_{sw_1}) \qquad \forall s, w_1 \tag{13}$$

$$wa_{sw_1} = \frac{I^{-}_{sw_1}}{\lambda_{sw_1}}, \lambda_{sw_1} \neq 0 \qquad \forall s, w_1 \tag{14}$$

$$\bar{\tau}_{sw_2} = \sum_{w_1, y^{(1)}_{sw_1w_2}>0} (\tau_{sw_1w_2} + wa_{sw_1}) \qquad \forall s, w_2 \tag{15}$$

$$I^{+}_{sw_2} = \sum_{j_s=1}^{S^0_{sw_2}} j_s \times \frac{e^{-\lambda_{sw_2}\bar{\tau}_{sw_2}} (\lambda_{sw_2}\bar{\tau}_{sw_2})^{S^0_{sw_2}-j_s}}{(ST_{sw_2}-j_s)!} \qquad \forall s, w_2 \tag{16}$$

$$I^{-}_{sw_2} = I^{+}_{sw_2} - (S^0_{sw_2} - \lambda_{sw_2}\bar{\tau}_{sw_2}) \qquad \forall s, w_2 \tag{17}$$

$$I^0_{sw_2} + \sum_{w_1} y^{(1)}{}_{sw_1w_2} + \sum_{r} y^{(2)}{}_{srw_2} = S^0_{sw_2} + \sum_{c} z^{(1)}{}_{sw_2c} \qquad \forall s, w_2 \qquad (18)$$

$$I^0_{sw_1} + \sum_{s'} x^{(1)}{}_{ss'w_1} = S^0_{sw_1} + \sum_{r} w_{sw_1r} + \sum_{w_2} y^{(1)}{}_{sw_1w_2} \qquad \forall s, w_1, \sum_{s_1} p_{ss_1} > 0 \qquad (19)$$

$$I^0_{sw_1} + \sum_{s'} x^{(1)}{}_{ss'w_1} + \sum_{r} x^{(2)}{}_{srw_1} = S^0_{sw_1} + \sum_{w_2} y^{(1)}{}_{sw_1w_2} \qquad \forall s, w_1 \qquad (20)$$

$$\sum_{d} y''_{sid} = \sum_{c} (1 - G_{si}) \times x'_{sci} \qquad \forall s, i \qquad (21)$$

$$\sum_{r} y'_{sir} = \sum_{c} G_{si} \times x'_{sci} \qquad \forall s, i \qquad (22)$$

$$\sum_{i} y'_{sir} = \sum_{w_1} x^{(2)}{}_{srw_1} + \sum_{w_2} y^{(2)}{}_{srw_2} + \sum_{c} z^{(2)}{}_{src} \qquad \forall s, r \qquad (23)$$

$$\sum_{w_1} w_{sw_1r} + \sum_{d} z'_{sdr} \geq pu_{s_1s} \times \sum_{i} y'_{sir} + sr_{sr} \qquad \forall s, s_1, r \qquad (24)$$

$$\sum_{r} z'_{s_1dr} = \sum_{i} \alpha_{s_2d} \times p_{s_1s_2} \times y''_{s_2id} \qquad \forall s_1, s_2, d, p_{s_1s_2} > 0 \qquad (25)$$

$$\sum_{m} z''_{s_1dm} = \sum_{i} (1 - \alpha_{s_2d}) \times p_{s_1s_2} \times y''_{s_2id} \qquad \forall s_1, s_2, d, p_{s_1s_2} > 0 \qquad (26)$$

$$\sum_{w_1} x^{(1)}{}_{ss'w_1} \leq sc_{ss'} \qquad \forall s, s' \qquad (27)$$

$$\sum_{i} x'_{sci} = d_{sc} \qquad \forall s, c, \sum_{s_1} p_{ss_1} = 0 \qquad (28)$$

$$\sum_{i} y'_{sir} \leq M \times cp_{rs} \qquad \forall s, r \qquad (29)$$

$$\sum_{s} \sum_{i} rt_{sr} \times y'_{sir} \leq cap_r \qquad \forall r \qquad (30)$$

$$\frac{\sum_{s'} \sum_{w_1} df_{ss'} x^{(1)}{}_{ss'w_1}}{\sum_{w_1} \sum_{s'} x^{(1)}{}_{ss'w_1}} \leq md_s \qquad \forall s \qquad (31)$$

$$\begin{aligned}
&x'_{sci} \geq 0, int && \forall s, c, i \\
&y'_{sir} \geq 0, int && \forall s, i, r \\
&y''_{sid} \geq 0, int && \forall s, i, d \\
&z'_{sdr} \geq 0, int && \forall s, d, r \\
&z''_{sdm} \geq 0, int && \forall s, d, m \\
&x^{(1)}_{ss'w_1} \geq 0, int && \forall s, s', w_1 \\
&x^{(2)}_{srw_1} \geq 0, int && \forall s, r, w_1 \\
&y^{(1)}_{sw_1w_2} \geq 0, int && \forall s, w_1, w_2 \\
&y^{(2)}_{srw_2} \geq 0, int && \forall s, r, w_2 \\
&z^{(1)}_{sw_2c} \geq 0, int && \forall s, w_2, c \\
&z^{(2)}_{src} \geq 0, int && \forall s, r, c \\
&S^0_{sw} \geq 0, int && \forall s, w \\
&I^+_{sw}, I^-_{sw} \geq 0 && \forall s, w
\end{aligned} \qquad (32)$$

Constraint (9) ensures the demand to be met. Constraint (10) calculates the shipments from each central warehouse, and constraint (11) presents each local warehouse's demand. Constraints (12)-(17) show the METRIC model. Constraints (12) and (13) express expected on-hand inventory and shortage. The average waiting time of replenishment in the central warehouse is calculated using little law in constraint (14). The waiting time of replenishment for local warehouses is represented in constraint (15). Expected on-hand and shortage inventory in local warehouses are calculated by Equations (16) and (17). Constraints (18) and (19) ensure the balance of flows in local and central warehouses, respectively. Eq. (18) is related to the balance of flows of the spare parts. It ensures that the output of repair centers be equal to the number of spare parts entered. Constraint (19) expresses the balance of

equipment, and constraint (20) is the balance of spare parts in central warehouses. Constraints (21) and (22) show the balance of flows in inspection centers. Constraint (23) expresses the equality of input and output flow of the equipment in repair centers. Constraint (24) expresses the amount of spare parts needed for repairing equipment in repair centers. The balance of flow in disassembly centers is represented in constraints (25) and (26). The maximum capacity of suppliers is expressed in constraint (27). Reverse flow comes from end-user to inspection shown in constraint (28), that is the flow of defective equipment. Constraint (29) ensures the assignment of equipment to the repair center considering repair centers' capability. Then, constraint (30) and (31) specifies the maximum capacity of repair centers and defect allowed for each spare part. Finally, constraint (32) shows the domain of the decision variables.

5. Case Study

Oil is a strategic product, especially in Iran, which composes a prominent part of overall revenues. Iran owns about 9.5% of the global reserves, which equals 45.7 Billion dollars, about 4% of the total world oil revenue. Therefore, well-organized maintenance and repair planning is vital in such an industry to enhance the production level. Several resources are utilized to perform operations, such as human resources, material, and tools. Spare parts are essential materials used for repair and maintenance operations (MRO) of equipment. Proper inventory and supply planning can improve the reliability of the systems by supporting MRO.

The National Iranian South Oilfields Company (NISOC), as the largest subsidiary of the National Iranian Oil Company, spreads over more than 400,000 square kilometers from Bushehr province to northern Khuzestan, which includes about 80% of the total crude oil and 16% of the total gas production. In this territory, there are vast fields such as Ahwaz, Gachsaran, Marun, Aghajari, Kranj, and Bibi Hakimeh, and Rag Sefid, which are presented in Figure 2.

This territory is considered the under-study field, including two central warehouses, five local warehouses, and ten installation bases (end-users). Central warehouses are considered to exist in Ahwaz and Gachsaran. Also, local warehouses exist in all the provinces. Three inspection centers, three repair centers, and three disassembly centers are specified in this area. Repair centers are located close to the central warehouses. Additionally, end-users are near the local warehouses.

Gas turbines are used in a significant portion of the oil industry and provide mechanical energy from the chemical energy of the combustion process. They are too expensive and need precise maintenance planning. Two types of low-demand, expensive equipment of Gas turbines are selected, including turbine burner and stator, shown in Figure 3. The spare parts may be different in various turbines.

Burner or combustor is equipment in which the fuel is combined with high-pressure air and burned. The process generates high-temperature exhaust gas resulting in thrust. Stator and burner are repairable equipment that are composed of other spare parts that can be repairable or non-repairable. The repairability of the equipment is examined in the inspection center.

The repairable equipment is heading to repair centers according to the capability and capacity of repair centers, and the rest of the equipment moves to disassembly centers. The components (i.e. the spare parts) of the equipment are presented in Table2.

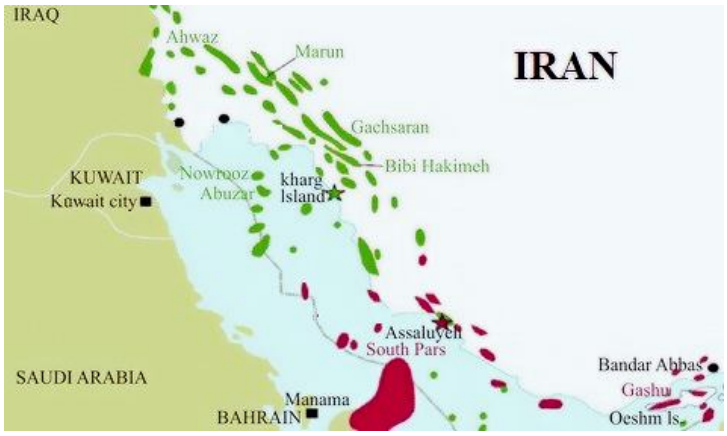
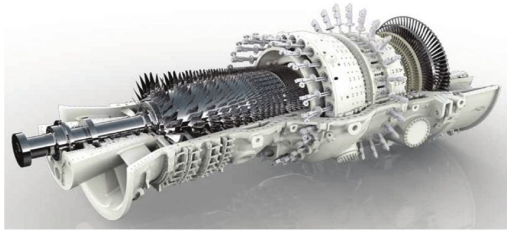


Fig. 2. The territory of the National Iranian South Oilfields Company



(a)

(b)

(c)

Fig. 3. (a) Gas turbine, (b) Turbine Stator blades & (c) burner

Tab. 2. Spare parts of the equipment

	Turbine Burner	Turbine Stator
1	Panel pak filter	Flexible joint
2	Solenoid valve	Filtometer
3	Washer	Solenoid switch
4	Swirler cone	Multiduty air filter
5	Flame tube	

The available capacity of the repair centers is 3000 Man-hour, which limits the number of repairs. Each repair and disassembly operation charges a specific cost, including material, human resources, tools, and energy. The expected repair and disassembly costs can be seen in Table 3. Also, the expected repair time is 50 and 30 Man-hour for the turbine burner and stator, respectively. All the repair centers are qualified for the repair operations of the turbine burner and stator.

Tab. 3. Repair & disassembly costs (USD)

Equipment	Repair center	Disassembly center
Turbine Burner	75,000	7,500
Turbine Stator	87,500	5,000

The equipment and spare parts are supplied from various suppliers that differ in capacity, price, and defect rate, shown in Table 4. Additionally, the maximum defect rates for equipment and spare parts are respectively 0.05 and 0.1.

Tab. 4. Suppliers and the details

# No.	Equipment/Spare parts	Supplier 1			Supplier 2			Supplier 3		
		Capacity	Price(USD)	Defect rate	Capacity	Price (USD)	Defect rate	Capacity	Price (USD)	Defect rate
1	Turbine Burner	20	290,000	0.01	20	300,000	0.01	10	500,000	0.01
2	Panel pak filter	100	757.5	0.1	50	800	0.1	50	750	0.1
3	Solenoid valve	50	7627.5	0.05	20	7532.5	0.05	20	7550	0.05
4	Washer	500	85	0.01	500	112.5	0.01	500	125	0.01

5	Swirler cone	50	2075	0.01	20	2250	0.01	20	2500	0.01
6	Flame tube	10	15,000	0.01	5	22850	0.01	5	22850	0.01
7	Turbine Stator	10	875,000	0.01	5	750,000	0.01	5	1000,000	0.01
8	Flexible joint	250	500	0.01	100	625	0.01	100	750	0.01
9	Filtometer	1000	250	0.02	500	500	0.01	500	525	0.02
10	Solenoid switch	500	50	0.1	100	42.5	0.1	300	55	0.1
11	Multiduty air filter	500	75	0.1	500	75	0.1	500	75	0.1

Initial inventory of central and local warehouses and the holding costs can be seen in Table 5. Also, holding costs in repair centers are the same as the warehouses. There is no initial inventory available in repair centers. The demands for the equipment and spare parts make the flow throughout the forward and reverse supply chain. Demands of installation bases are presented in Table 6.

Tab. 5. Initial inventory and holding costs in warehouses

	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 (%)

Tab. 6. Demands of end-users (installation bases)

Equipment/ Spare parts	End-users (installation bases)									
	1	2	3	4	5	6	7	8	9	10
Turbine Burner	3	0	1	0	2	0	1	1	1	1
Panel pak filter	1	0	1	0	0	0	1	0	0	0
Solenoid valve	1	0	0	0	1	0	0	0	1	1
Washer	1	0	0	0	0	0	0	0	0	0
Swirler cone	0	0	0	0	0	0	0	1	0	0
Flame tube	0	0	0	0	1	0	0	0	0	0
Turbine Stator	1	1	0	0	1	2	0	0	0	1
Flexible joint	0	0	0	0	0	1	0	0	0	0
Filtometer	0	1	0	0	0	0	0	0	0	0
Solenoid switch	0	0	0	0	1	0	0	0	0	1
Multiduty air filter	1	0	0	0	0	1	0	0	0	0

The proportion of repairability for the equipment determines the amount of output in inspection centers. The parameters in Table 7 depends on the lifetime of equipment and spare parts, repair expertise, and company policies.

Tab. 7. Proportion of equipment repairability

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

Raw material manufacturers purchase non-repairable spare parts at salvage value shown in Table 8. Usable spare parts of disassembled equipment are specified in Table 9.

Tab. 8. Salvage value (USD)

Equipment/ Spare part	Salvage value
Turbine Burner	29000
Panel pak filter	7.575
Solenoid valve	76.275
Washer	0.85
Swirler cone	20.75
Flame tube	150
Turbine Stator	87500
Flexible joint	5
Filtometer	2.5
Solenoid switch	0.5
Multiduty air filter	0.75

Tab. 9. Usable spare parts

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

Repairable equipment proceeds to repair centers, which may be serviced in different ways, such as repairing or substituting spare parts. These services include other operations, including lubrication, cleaning, and the like. The probability of demand for the spare parts in each equipment can be seen in Table 10.

Tab. 10. Probability of demand for the spare parts

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

6. Computations and Results

To solve the mathematical model, we should first simplify the non-linear constraints that complicate the model. Eqs. (12) and (16) compute the average on-hand inventory, but the variable upper bound increases the complexity. The method described in the following simplifies these equations. Eq. (33) is the summation of some terms over a variable. This method adds Eqs. (34)-(37) to decrease the complexity of Eq. (33) by substituting a parameter instead of the variable on the upper bound. Also, We present a procedure in the following as shown in Figure 4, that uses an initial value for the upper bound to solve the model. We change this value until the desired results are obtained. The case study data is used to solve the model using Baron solver in GAMS 24.7.4 on a Laptop with Intel Core i5 CPU @ 2.5 GHz and 16 GBs Ram.

$$y = \sum_{i=0}^{x} f(i) \tag{33}$$
$$x \geq 0, int$$
$$x - i + 1 \leq M \times b_i \tag{34}$$
$$i - x \leq M \times (1 - b_i) \tag{35}$$
$$y = \sum_{i=0}^{n} b_i f(i) \tag{36}$$
$$x \geq 0, int$$
$$b_i \in \{0,1\} \tag{37}$$

Considering the method, we substitute Eqs. (12)-(16) with (38)-(41).

The solution method results in total costs of 1.26×10^8. Stock levels of equipment and spare parts are presented in Table 11. The stock level depends on the initial inventory and the demand for equipment and spare parts, as is clear.

Tab. 11. Stock levels in warehouses

warehouses		Stock levels										
		1	2	3	4	5	6	7	8	9	10	11
Central	1	0	7	0	15	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0
Local	1	0	0	2	13	0	3	2	0	0	0	0
	2	0	0	0	15	0	0	0	3	0	0	0
	3	0	0	0	0	0	0	0	1	0	0	0
	4	0	15	8	15	0	13	15	12	0	0	0
	5	0	15	0	15	1	0	0	14	2	1	0

$$I_{sw_1}^{+} = \sum_{j_s=1}^{n_{sw_1}} b_{sw_1} \times (j_s \times \frac{e^{-\lambda_{sw_1}\tau_{sw_1}}(\lambda_{sw_1}\tau_{sw_1})^{S_{sw_1}^0 - j_s}}{(S_{sw_1}^0 - j_s)!}) \tag{38}$$
$$S_{sw_1}^0 - i_{sw_1} + 1 \leq M \times b_{sw_1} \tag{39}$$
$$i_{sw_1} - S_{sw_1}^0 \leq M \times (1 - b_{sw_1}) \qquad i_{sw_1} = 0, \ldots, n_{sw_1} \tag{40}$$
$$b_{sw_1} \in \{0,1\} \tag{41}$$

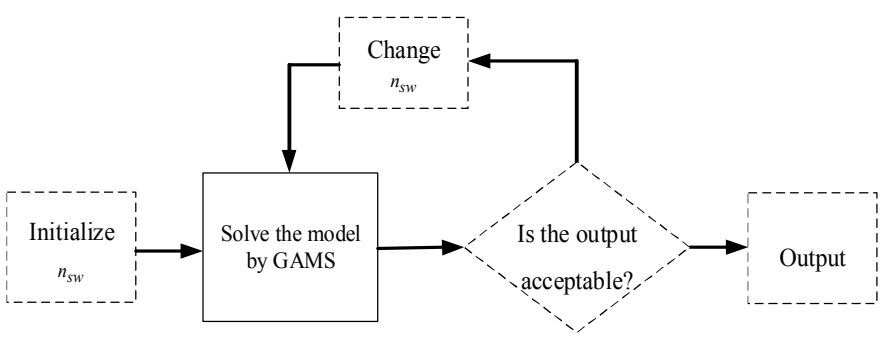


Fig. 4. Solution methodology

Non-repairable equipment is disassembled in disassembly centers then the usable spare parts are sent to be stocked in repair centers for use in the repair operation of the defective equipment. The stock level of spare parts in repair centers can be seen in Table 12.

Tab. 12. Stock levels in repair centers

Repair center	Washer	Swirler cone	Flexible joint	Filtometer	Multiduty air filter
1	1	0	2	0	0
2	0	2	0	3	2
3	36	0	1	0	0

Order assignment to the suppliers considering criteria (such as defect rate, price, and capacity of suppliers) are given in Table 13.

Tab. 13. Supplier selection

Supplier	Central warehouse 2 Turbine burner
1	1

The assignment of equipment from inspection centers to repair centers subordinates from the repair capability and capacity of repair centers, which is shown in Table 14. The rest of the equipment is moved to disassembly centers, shown in Table 15.

Tab. 14. Assignment of equipment to repair centers

Inspection centers	Equipment	Repair centers	
		1	3
1	Turbine burner	0	8
	Turbine stator	1	0
2	Turbine stator	2	0

Tab. 15. Assignment of equipment to disassembly centers

Inspection centers	Spare parts	disassembly centers
		1
1	Turbine burner	2
	Turbine stator	1
2	Turbine stator	2

The results also show the amount of non-repairable equipment that will be disposed or moved to repair centers. Tables 16 & 17 presents the amount of usable and unusable spare parts, respectively.

Tab. 16. Usable spare parts

Spare parts	Disassembly center	Repair centers		
		1	2	3
Solenoid valve	1	0	0	2
Swirler cone	1	0	2	0
Flexible joint	1	3	0	0
Filtometer	1	0	3	0
Solenoid switch	1	1	2	0

Tab. 17. Unusable spare parts

Spare parts	Disassembly center	Raw Material Manufacturers
		1
Panel pak filter	1	2
Washer	1	2
Flame tube	1	2
Multiduty air filter	1	3

7. Sensitivity Analysis

In this section, we discuss the effect of changes in the parameters such as the proportion of equipment repairability, lead-time, repair, shortage, and holding costs.

The fluctuations in the repairability proportion impact the total cost that is illustrated in Figure 5. It can be deduced that the total cost is minimum, where the proportion of repairability is one, i.e., all the burners are repaired. Additionally, Table 18 presents the fluctuation of the total cost. The uptrend in costs starts where 20% of equipment is repaired and continues up to 60%.

In this range, by increasing the repairability proportion, the total cost increases due to repair cost, but the more the equipment is repaired, the less the flow of disassembled spare parts will be. To supply spare parts, more orders from the central warehouse are released, which affect the increasing trend of the total cost. The decreasing trend begins after the proportion of 0.6, which means it is economical to repair more than 60% of burners.

Tab. 18. Total costs (USD) vs. change in the repairability proportion for the burner

Repairability proportion	0	0.2	0.4	0.6	0.80	1
Total cost	1.95E+08	1.39E+08	2.26E+08	5.75E+08	1.26E+08	5.28E+07

Changing the proportion of repairability also affects the stock levels of repair centers, presented in Table 19. Repair centers use spare parts to repair equipment, which reduces the stock level. Additionally, the more equipment is assigned to repair centers, the less the flow of spare parts from disassembly centers is.

Figure 6 shows the decreasing trend of the stock level of spare parts 3 (solenoid valve) and 5 (swirler cone) in repair centers. The stock level of the washer increases for the proportion of more than 0.8. It can be interpreted that the demand for this spare part is insignificant.

Tab. 19. Stock level in repair centers along with the proportion of repairability of burner

Proportion of repairability	Spare part		
	3	4	5
1	10	39	10
0.8	8	39	8
0.6	6	39	6
0.4	3	39	4
0.2	0	37	2
0	0	64	0

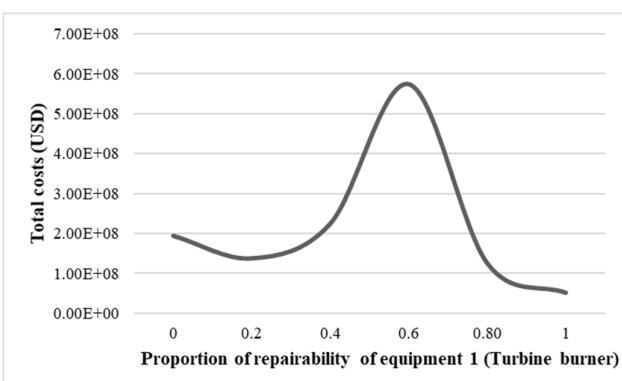


Fig. 5. Total cost when the proportion of repairability of burner changes

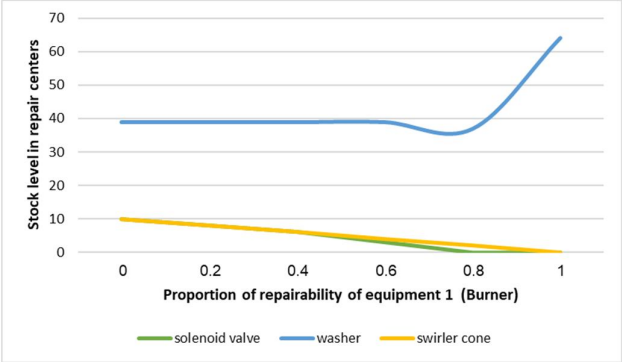


Fig. 6. Stock level in repair centers when the proportion of repairability of burner changes

Tab. 20. Order from suppliers vs. change in the proportion of repairability of burner

Proportion of repairability of burner	burner
1	10
0.8	8
0.6	5
0.4	4
0.2	1
0	0

Figure 7 illustrates the order from suppliers, which fluctuates with the proportion of repairability. When all the burners are repaired, the amount of orders from suppliers is minimum, which justifies the importance of repairing instead of purchasing new-branded equipment. Increasing the proportion of repairability reduces the total order quantity. Table 20 presents the details of total orders from suppliers regarding the various proportion of repairability for the burner. Figure 8 illustrates the change in Holding Cost Per Unit (HCPU) and its effect on the total cost. By increasing HCPU, total cost almost increases, and vice versa. The total cost's maximum value can be observed at 0.6, while the total cost decreases in other points. Table 21 presents the fluctuation of the HCPU in other points. As total cost reached the maximum point, the stock level starts to decrease to avoid higher holding costs.

Tab. 21. Total cost vs. fluctuation in HCPU

HCPU	0	0.15	0.4	0.6	0.8	1
Total cost	5.25E+07	1.26E+08	1.39E+08	1.68E+08	1.40E+08	1.39E+08

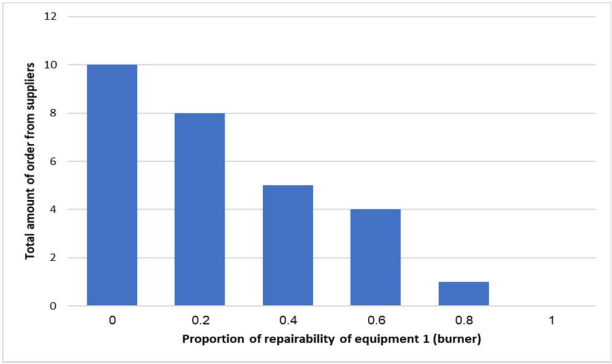


Fig. 7. Total orders vs. the fluctuation in the proportion of repairability of burner

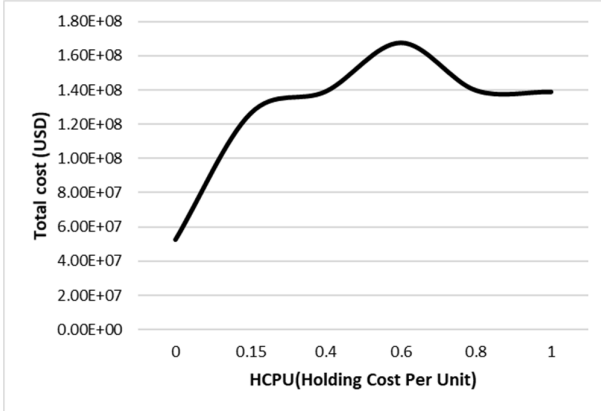


Fig. 8. Total cost vs. HCPU

Fluctuation in the proportion of repairability of stator is shown in Figure 9, and the details are presented in Table 22. The minimum value of the total cost is obtained, where one-third of the stator is repaired. Repairing all the stator causes the maximum total cost. The jumps happen due to changes in stock level and orders from suppliers.

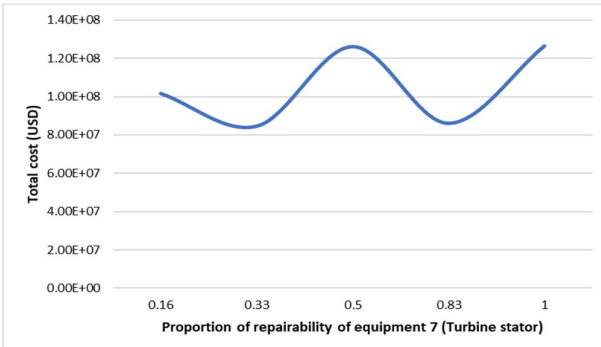


Fig. 9. Total cost vs. HCPU

Tab. 22. Total costs vs. change in the proportion of repairability of equipment 7 (Stator)

Proportion of repairability of Stator	0.16	0.33	0.5	0.83	1
Total cost (USD)	1.02E+08	8.47E+07	1.26E+08	8.62E+07	1.27E+08

The stock level of the spare parts of the stator decreases as the proportion of repairability increases, shown in Figure 10. More spare parts are used to repair the equipment by increasing the proportion, which causes a decrease in the stock level.

Tab. 23. Stock level vs. change in the proportion of repairability of equipment 7 (Stator)

Proportion of repairability of stator	Flexible joint	Filtometer	Solenoid switch
0.16	5	5	5
0.33	4	4	4
0.5	3	3	2
0.83	0	1	0
1	0	0	0

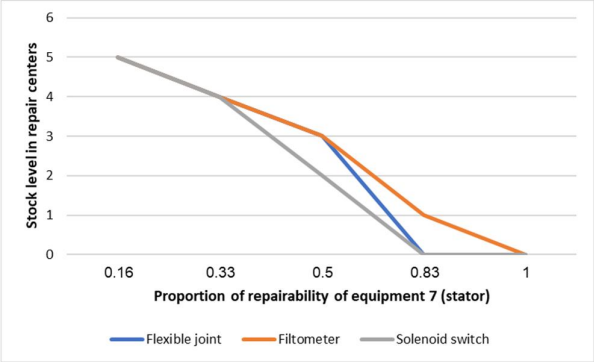


Fig. 10. Stock level in repair centers when the proportion of repairability of stator changes

Repair cost constitutes a prominent part of the total cost; Therefore, any repair cost changes can significantly affect the total cost, as shown in Figure 11. This figure illustrates that the total cost is maximum when the repair cost takes the original value. On other points, total costs decrease while repair cost changes. The behavior of the total cost and expected shortage are demonstrated in Figure 12.

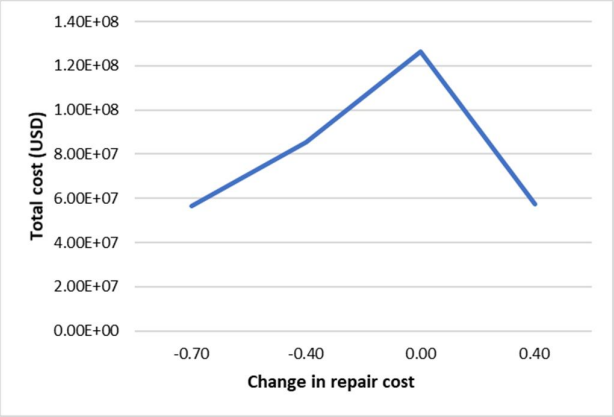


Fig. 11. Total cost vs. change in repair cost

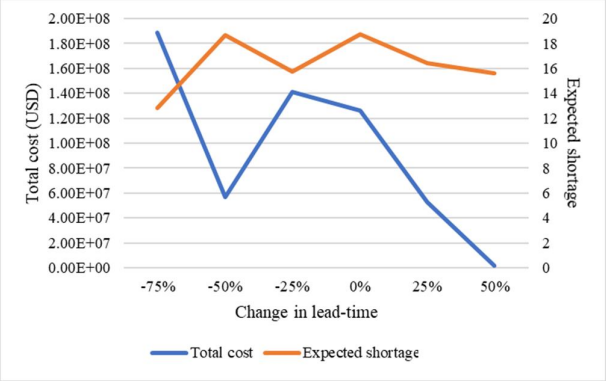


Fig. 12. Total cost and expected shortage along with lead-time

Tab. 24. Total cost vs. change in the repair cost

Repair cost change	Repair cost of burner	Repair cost of stator	Total cost (USD)
-0.70	22500	26250	5.64E+07
-0.40	45000	52500	8.53E+07
0.00	75000	87500	1.26E+08
0.40	105000	122500	5.73E+07

Lead-time and expected shortage change in the same way. As lead-time decreases, there are some slight changes in the expected shortage, but it finally decreases. Since the lead-time reduces, the waiting time and the average shortage decrease. The lower lead-time imposes a lower waiting time, which causes higher costs. Since the shortage imposes incredible costs, increasing lead-time generally results in an upward shortage due to a decrease in inventory level. Accordingly, total cost decreases since consuming the inventory is more economical than ordering.

Tab. 25. Total cost & expected shortage vs. lead-time

Change in lead-time	-75%	-50%	-25%	0	25%	50%
Total cost (USD)	1.89E+08	5.70E+07	1.41E+08	1.26E+08	5.28E+07	1.74E+06
Expected shortage	12.8	18.6	15.7	18.7	16.3	15.6

The analyses help obtain managerial insights, which are listed as follows:

- The policies for inventory management of various equipment and spare parts should not be the same due to differences in demands and values;
- Lead-time profoundly affects the on-hand inventory so, considering the optimal location of warehouses and the covering distances can reduce cost (such as transportation and inventory costs) and reduce shortages;
- Repair or purchase is an important question that can increase or decrease costs to a degree of extent. The trade-off between the costs may come enlightening
- The answer to the question of repairing or not can be helpful to specify which spare parts to purchase;
- It is noteworthy that not repairing (i.e. disassembling) the equipment can sometimes be a better solution not only to take the advantage of purchase to repair but also for using their spare parts in other repair operations and salvage earnings;
- Analysis of stock level is a multifold problem, which depends on various factors, especially in a forward-reverse supply chain. Decision-makers should consider the type of equipment or spare parts, purchase cost, lead-time, repair cost, and holding costs and analyze the trade-off among these factors to make the best decision.

8. Conclusion and Future Research Opportunity

This paper considers a forward-reverse repairable spare part supply chain. In the proposed model, decisions are made regarding stock level in repair centers and warehouses, order assignment, and optimal flow between facilities. The model also considers the uncertainty in demand during the lead-time, which makes the model more applicable. A case study of the National Iranian South Oilfields Company is presented to validate the model. Through numerical analysis, few insights are obtained, which can be helpful for decision-makers. According to the results, it is found that the inventory management policies for each equipment and spare part should be different due to value, demand, and responsiveness level. We observe a trade-off between purchasing and repairing, which differs from one equipment to another. To minimize shortages, holding inventory imposes high costs on industries, but maintaining an optimal stock level of spare parts and equipment can satisfy demands while reducing holding costs. This goal can be reached by repairing equipment and using usable spare parts from disassembled equipment. The optimal assignment of central warehouses to local warehouses while considering the optimal location can provide significant cost savings through low-cost transportation, enhancing travel time between these facilities. Also, optimizing the repair cost can significantly affect the total cost; e.g., a 40% cut down in repair cost can reduce the total cost up to 32%. Also, A decrease in lead-time can have a noticeable impact on total cost and expected shortages.

In this paper, we assumed that warehouses are located in predefined locations. Also, expensive

equipment and spare parts with low demand are investigated in a single extended period. Further research can consider simultaneous low and high-demand equipment and spare parts and compare the present model results. Also, other directions are such as considering uncertain lead-time, location-inventory decisions, and different replenishment policies.

References

[1] B. C. Giri, A. Chakraborty, and T. Maiti, "Pricing and return product collection decisions in a closed-loop supply chain with dual-channel in both forward and reverse logistics," *Journal of manufacturing systems*, Vol. 42, (2017), pp. 104-123.

[2] V. D. R. Guide, T. P. Harrison, and L. N. Van Wassenhove, "The challenge of closed-loop supply chains," *Interfaces*, Vol. 33, No. 6, (2003), pp. 3-6.

[3] J. Heydari, K. Govindan, and A. Jafari, "Reverse and closed loop supply chain coordination by considering government role," *Transportation Research Part D: Transport and Environment*, Vol. 52, (2017), pp. 379-398.
doi: https://doi.org/10.1016/j.trd.2017.03.008.

[4] W. Lee, S.-P. Wang, and W.-C. Chen, "Forward and backward stocking policies for a two-level supply chain with consignment stock agreement and stock-dependent demand," *European Journal of Operational Research*, Vol. 256, No. 3, (2017), pp. 830-840.

[5] A. Pedram, N. B. Yusoff, O. E. Udoncy, A. B. Mahat, P. Pedram, and A. Babalola, "Integrated forward and reverse supply chain: A tire case study," *Waste Management*, Vol. 60, (2017), pp. 460-470.
doi:https://doi.org/10.1016/j.wasman.2016.06.029.

[6] R. Carrasco-Gallego, E. Ponce-Cueto, and R. Dekker, "Closed-loop supply chains of reusable articles: a typology grounded on case studies," *International Journal of Production Research*, Vol. 50, No. 19, (2012), pp. 5582-5596.

[7] M. Alborzi, *Management information system*, 2nd ed., Vol. 1. Andishehaye goharbar, (2019).

[8] M. E. Hora, "The unglamorous game of managing maintenance," *Business Horizons*, Vol. 30, No. 3, (1987), pp. 67-75.

[9] W. Wilson, "What's the real cost of spare parts inventory?" Resource Library, Jun. 18, 2020. [Online]. Available: https://www.lce.com/Whats-the-real-cost-of-spare-parts-inventory-1189.html

[10] M. M. Paydar, V. Babaveisi, and A. S. Safaei, "An engine oil closed-loop supply chain design considering collection risk," *Computers & Chemical Engineering*, Vol. 104, (2017), pp. 38-55.
doi: 10.1016/j.compchemeng.2017.04.005.

[11] V. Jayaraman, V. D. R. Guide, and R. Srivastava, "A closed-loop logistics model for remanufacturing," *Journal of the Operational Research Society*, Vol. 50, No. 5, (1999).
doi: 10.1057/palgrave.jors.2600716.

[12] C.-J. Chung and H.-M. Wee, "Green-component life-cycle value on design and reverse manufacturing in semi-closed supply chain," *International Journal of Production Economics*, Vol. 113, No. 2, (2008).
doi: https://doi.org/10.1016/j.ijpe.2007.10.020.

[13] P. Sasikumar, G. Kannan, and A. N. Haq, "A multi-echelon reverse logistics network design for product recovery—a case of truck tire remanufacturing," *The International Journal of Advanced Manufacturing Technology*, Vol. 49, No. 9-12, (2010).

[14] B. Vahdani, R. Tavakkoli-Moghaddam, M. Modarres, and A. Baboli, "Reliable design of a forward/reverse logistics network under uncertainty: A robust-M/M/c queuing model," *Transportation Research Part E: Logistics and Transportation Review*, Vol. 48, No. 6, (2012), pp. 1152-1168.
doi: https://doi.org/10.1016/j.tre.2012.06.002.

[15] X. He and W. Hu, "Modeling Relief Demands in an Emergency Supply Chain System under Large-Scale Disasters Based on a Queuing Network," *The Scientific World Journal*, Vol. 2014, (2014), p. 195053.
doi: 10.1155/2014/195053.

[16] S. M. Hatefi, F. Jolai, S. A. Torabi, and R. Tavakkoli-Moghaddam, "Reliable design of an integrated forward-revere logistics network under uncertainty and facility disruptions: a fuzzy possibilistic programing model," *KSCE Journal of Civil Engineering*, Vol. 19, No. 4, (2015), pp. 1117-1128.

[17] A. Mirakhorli, "Fuzzy multi-objective optimization for closed loop logistics network design in bread-producing industries," *The International Journal of Advanced Manufacturing Technology*, Vol. 70, No. 1-4, (2014).

[18] A. Choudhary, S. Sarkar, S. Settur, and M. K. Tiwari, "A carbon market sensitive optimization model for integrated forward–reverse logistics," *International Journal of Production Economics*, Vol. 164, (2015), pp. 433-444.

[19] K. Sarrafha, A. Kazemi, and A. Alinejad, "Designing and optimizing the integrated production-distribution planning problem in a multi-level supply chain network: a multi-objective evolutionary approach," Vol. 26, No. 3, (1394).

[20] M. Zohal and H. Soleimani, "Developing an ant colony approach for green closed-loop supply chain network design: a case study in gold industry," *Journal of Cleaner Production*, Vol. 133, (2016), pp. 314-337.

[21] A. Pedram, N. B. Yusoff, O. E. Udoncy, A. B. Mahat, P. Pedram, and A. Babalola, "Integrated forward and reverse supply chain: A tire case study," *Waste Management*, Vol. 60, (2017), pp. 460-470.
doi:https://doi.org/10.1016/j.wasman.2016.06.029.

[22] H. Ahmadi kurd, S. Yaghobi, and A. hakim Taghan zadeh, "A robust optimization Model for designing reverse water network for Agricultural comsumption (Case Study: Tehran Province)," Vol. 28, No. 4, (1396).

[23] M. Yadollahinia, E. Teimoury, and M. M. Paydar, "Tire forward and reverse supply chain design considering customer relationship management," *Resources, Conservation and Recycling*, Vol. 138, (2018), pp. 215-228.
doi:https://doi.org/10.1016/j.resconrec.2018.07.018.

[24] J. Kim, B. D. Chung, Y. Kang, and B. Jeong, "Robust optimization model for closed-loop supply chain planning under reverse logistics flow and demand uncertainty," *Journal of Cleaner Production*, Vol. 196, (2018), pp. 1314-1328.
doi:https://doi.org/10.1016/j.jclepro.2018.06.157.

[25] L. T. T. Doan, Y. Amer, S.-H. Lee, P. N. K. Phuc, and L. Q. Dat, "A comprehensive reverse supply chain model using an interactive fuzzy approach – A case study on the Vietnamese electronics industry," *Applied Mathematical Modelling*, Vol. 76, (2019), pp. 87-108.
doi: https://doi.org/10.1016/j.apm.2019.06.003.

[26] B. M. Tosarkani and S. H. Amin, "An environmental optimization model to configure a hybrid forward and reverse supply chain network under uncertainty," *Computers & Chemical Engineering*, Vol. 121, (2019), pp. 540-555.
doi:https://doi.org/10.1016/j.compchemeng.2018.11.014.

[27] A. Sadeghi, H. Mina, and N. Bahrami, "A mixed integer linear programming model for designing a green closed-loop supply chain network considering location-routing problem," *International Journal of Logistics Systems and Management*, Vol. 36, No. 2, (2020).

[28] M. R. Gholamian and M. Heydari, "An inventory model with METRIC approach

in location-routing-inventory problem," *ADVANCES IN PRODUCTION ENGINEERING & MANAGEMENT*, Vol. 12, No. 2, (2017), pp. 115-126. doi: 10.14743/apem2017.2.244.