Sādhanā (2021)46:59
https://doi.org/10.1007/s12046-021-01579-3

Scenario-based two-stage stochastic programming for a Hybrid Manufacturing-Remanufacturing System with the uncertainty of returns, quality and demand

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MS received 2 September 2019; revised 14 September 2020; accepted 12 January 2021

Abstract. This paper addresses the optimization of make-to-order hybrid manufacturing - remanufacturing system to make capacity and inventory decisions jointly along with production decisions. The proposed system considers a common production facility and the same assembly/disassembly line to perform manufacturing and remanufacturing operations simultaneously. The current study takes into account an environment where new and remanufactured (reman) products competing to each other that is, the common demand stream for both products but different selling prices. Furthermore, the relative capacity consumed by remanufacturing over the manufacturing is explained in two ways, namely less capacity intensive case and more capacity intensive case. Differently, from previous studies, we consider a scenario with a discounted selling price for reman products, shortage penalty costs, lost sales, disposal and uncertainty in demand, amount and yield of returns. Hence, to handle those uncertainties, a scenario-based stochastic programming model in a two-stage setting is presented. In the first stage, the raw material inventory and production capacity levels are planned and in the second stage, the production, inventory and disposal decisions are determined by balancing overage and underage costs. The results indicate that net values associated with new and reman products can be decisive in choosing either manufacturing or remanufacturing.

Keywords. Capacity investment; inventory planning; remanufacturing; two-stage stochastic programming; scenario-based approach.

1. Introduction

Many drivers like environmental legislation, corporate citizenship are pushing firms to incorporate returned products into the supply chain (SC) for recapturing the materials for economic and sustainability purposes [1]. To manage the returned products effectively, Reverse logistics can be used as a strategic tool by achieving operational efficiency and a sustainable supply chain. Reverse Logistics practices such as remanufacturing, recycling, reuse, and repair have been developed which are environmentally and economically sound to deal with the core returns after customer usage. Among these many popular initiatives, remanufacturing is playing a vital role for firms to differentiate themselves from competitors by adding value to their supply chains and reducing costs while catering the needs of environmental sustainability [2, 3].

Remanufacturing is "a process whereby value from used products is captured by recovering used components to bring such products to a new or like-new state" [4]. Remanufacturing of used products becomes an emergent business area due to economic and environmental reasons. Nowadays, both original equipment manufacturers (OEMs) and third parties (jobbers) are involved in remanufacturing activities, investing in many locations throughout the world. However, original equipment (OE) suppliers struggle to manage their remanufacturing business efficiently due to lack of a holistic framework for strategic remanufacturing decision-making across the globe. Companies dealing with OE service and the independent aftermarket, are identified the key strategic factors that influence remanufacturing mostly. These key strategic factors are such as design for remanufacturing, plant location, production systems, product planning, physical distribution and cooperation among remanufacturing stakeholders [5, 6].

Though Indian markets are at the infancy stage, they have huge potential and wealth generation for

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Published online: 24 March 2021

remanufacturing products. Some potential actions, like creating financial incentives to support remanufacturing, developing extended producer responsibility, are helping to improve/grow remanufacturing in India considering economic and environmental aspects. Indian Railways, the largest industry sector, is using remanufacturing for Engines, Bogie Frame, Loco under the frame at DMW, Patiala [7]. General Electric (GE) also using remanufacturing for engines, solar turbines, engineering and track services. Timken India Pvt. Ltd., a bearing manufacturing company is replacing new components by remanufacturing and repair to improve customer service level. It provides reconditioning services for rail bearings, axle boxes, and motor suspension units and also repairs and overhaul services for the engine, gear boxes, aerospace bearings and precision components.

In the present study, we consider a make-to-order hybrid manufacturing – remanufacturing (HMR) system with a common demand stream. The aim of the paper is to optimize capacity and inventory decisions simultaneously considering the uncertainty in demand, core returns and their yield. To account for uncertainty (demand, returns, and yield) in a reverse logistics setting, we present a scenario-based two-stage stochastic model for an HMR system. In this work, we also considered relative capacity consumed by remanufacturing to process core returns with respect to manufacturing.

The rest of the paper is structured in the following manner. In section 2, a summary of relevant literature is provided. Mathematical formulation, along with problem definition, is presented in section 3. Section 4 discusses the results found using a scenario-based approach for the developed model. In the last section, the paper ends with providing a conclusion and future directions.

2. Literature

There is an extensive stream of research on remanufacturing in the operations literature. The firms are started to procure the end-of-life (EOL) products to improve total profitability and customer service level. HMR systems have received growing attention in recent years due to substantiality issues [6, 7]. Wang and Zhang [8] studied remanufacturer's production strategy and developed decision models for differentiated market demand for new and reman products with capital constraint. The authors found that consumer preference and processing cost are key factors influencing remanufacturer's production strategy. A simple framework to find the optimal prices along with the corresponding profitability of manufacturing for a cellular telephone industry was developed by Guide Jr. *et al* [9]. They observed that the change in the slope or intercept of the demand curve has a huge impact on profit. Varying quality-dependent acquisition prices/return policy influence the quantity and quality of core returns, which further affects the profitability of remanufacturing in a production system.

A key element in a company's success is its capability to match supply (different types of capacity and inventory) to uncertain demand. There is an enormous literature on inventory control with product returns [10]. Laan *et al* [11] presented pull and push strategies for production planning and inventory control in hybrid systems. However, these strategies are not very useful in a situation where stochastic demand presents. Hence, to improve performance, Takahashi *et al* [12] considered an adaptive strategy into the pull strategy.

In literature, some studies only focused on production planning and lot-sizing decisions without inventory issues. On the contrary, some studies focused on inventory issues such as base stock, reorder point, economic order quantity without production planning [10, 12]. Benjaafar and ElHafsi [13] proposed a Markov decision process for inventory control and the optimal production of an assemble-to-order system with a single product and multiple customer classes. They found that heuristics are more effective for systems with lost sales than systems with backorders. To determine an optimal inventory policy, Zhang *et al* [14] presented a mathematical model for remanufacture-to-order system considering a third party working closely with the OEM. In a similar fashion, Gong and Chao [15] formulated the periodic review, capacitated inventory system with remanufacturing as a two-dimensional stochastic dynamic program to find the optimal control policy. Authors identified that the production priority always given to remanufacturing than manufacturing in systems with a remanufacturing capacity. Bulmus *et al* [16] presented a two-period deterministic model to study the effect of remanufacturing on capacity as well as production decisions.

Under demand uncertainty, capacity adjustments are discrete because capacity size is adjusted before the realisation of demand. So, there may be the presence of excess capacity or shortage of capacity due to the demand uncertainty. Mieghem [17] reviewed recent developments in capacity management and determining the optimal size and timing of the capacity adjustment and investment under uncertain demand. The author suggested that the capacity investment risk can be mitigated using financial and operational hedging. Mieghem and Rudi [18] proposed a newsvendor network to plan capacity investment and inventory jointly to maximise total net profit. They mentioned that, in newsvendor networks, lost sales are more amenable than backlogging as in most inventory settings.

From the above literature, it was found that most mathematical models of HMR systems did not consider the capacity investment and inventory planning simultaneously. Also, some researchers did not consider, the yield of core returns, the capacity intensity of remanufacturing, uncertainty in demand, core returns supply and yield. To overcome these, a two-stage stochastic programming for a make-to-order system is presented reflecting real-life industrial scenario.

3. Mathematical formulation

3.1 *Problem definition*

In the current study, we present a model for make-to-order, HMR system with two inventories (raw material and core returns) and one resource (limited capacity) (Figure 1). The new and reman products are produced from raw material, and core returns respectively with a joint resource capacity on the same assembly line in the system. Both new and reman products are used to fulfil the demand in the primary market only. If the demand is not fulfilled, then it will be lost sales to the firm with a penalty. Yield issues which are common in most remanufacturing firms, given not all cores are suitable for remanufacturing are considered in the model. Uncertainty in demand, returns and their yield is also considered to impose real-world problems. Furthermore, the capacity consumption by remanufacturing with respect to manufacturing is considered in two ways: less capacity intensive case and more capacity intensive case.

The model is formulated as integer linear programming to maximise the total expected profit and helps in making optimal decisions such as capacity, inventory levels along with production decisions.

3.1a *Assumptions*: The selling price of a reman product is always less than or equal to the selling price of the manufactured product.

Remanufacturing product has quality equal to specifications of the manufactured product.

Both products have the same lead time.

No backlog is allowed.

3.1b *Nomenclature*: The nomenclature including all fixed and uncertain parameters along with decision variables presented at the end of the manuscript.

3.1c *Mathematical model*: In this section, we present the mathematical models in both less and more capacity intensive cases.

3.2 *Objective function*

The objective is to maximize the total expected profit which includes revenue from the sale of the products and various costs such as acquiring cost for getting raw material and collecting core returns, capacity investment cost to facilitate operations, production costs to manufacture and remanufacture, shortage penalty costs, disposal cost to discard poor returns and inventory cost to hold raw material.

Maximize

$$\begin{aligned}\Phi(Q_n, Z, q_n, q_r) = \mathrm{E}_\xi[&P_n q_n + P_r q_r - C_{an} Q_n - C_{ar} Q_r \\ &- C_z Z - C_n q_n - C_r q_r - C_{sp} q_n - C_{sp} q_r \\ &- C_h q_n - C_w q_r]\end{aligned} \tag{1}$$

Now, the objective function is simplified and incorporated v_n and v_r which are net values associated with the new and remanufactured products respectively.

$$v_n = P_n - C_n + C_{sp} + C_h \quad v_r = P_r - C_r + C_{sp} + C_w$$

Further, the objective function (1) rewritten as

Maximize

$$\begin{aligned}&\Phi(Q_n, Z, q_n, q_r | y_r(\xi), Q_r(\xi), d(\xi)) \\ &\quad = (-C_z Z - (C_h + C_{an}) Q_n + \mathrm{E}_\xi[v_n q_n + v_r q_r])\end{aligned} \tag{2}$$

The objective (2) is to maximise the total expected profit that the firm will gain by producing products with available resources.

3.3 *Constraints*

In the current study, firstly we put the constraints to fulfill the demand as much as possible. Later, we incorporated business restrictions for the effective utilization of resources such as Capacity and Inventory available. The functionality of constraints is explained below in detail.

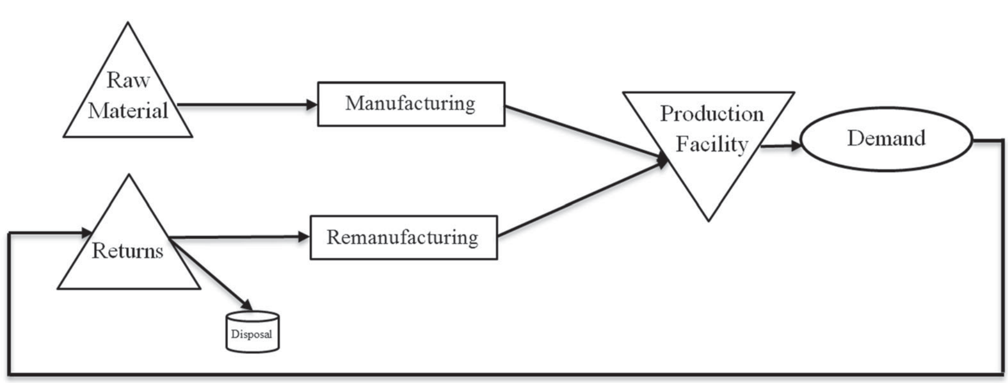

Figure 1. Hybrid manufacturing–remanufacturing system with a common demand stream.

$$q_n \quad - Q_n \leq 0 \tag{3}$$

$$q_r \quad \leq y_r(\xi) Q_r(\xi) \tag{4}$$

$$q_n + q_r \quad \leq d(\xi) \tag{5}$$

Constraint (3) is a restriction on raw material inventory that allows the production of new products up to its level. Constraint (4) is a restriction that allows the production of reman products up to core returns inventory level. Constraint (5) assures the production of the required amount of new and reman products to fulfil market demand. These constraints are the same in both cases (less capacity intensive and more capacity intensive). However, capacity constraints differ as follows.

3.4 *Capacity constraints in less capacity intensive case*

$$q_n + \alpha q_r - Z \leq 0 \tag{6}$$

Constraints (6) represents the consumption of capacity by new and reman products at the rate of one and α (where $0 \leq \alpha \leq 1$) respectively.

3.5 *Capacity constraints in more capacity intensive case*

$$q_n + \gamma^{-1} q_r - Z \leq 0 \tag{7}$$

Constraint (7) represents the consumption of capacity by new and reman products at the rate of one and γ^{-1}(where $0 \leq \gamma \leq 1$) respectively.

3.6 *Nature of variables*

$$Q_n, Z, q_n, q_r \geq 0 \tag{8}$$

3.1d *Two-stage stochastic linear programming:*

To handle the uncertainty effectively, we reformulated the model as a two-stage stochastic linear programming by considering *m* scenarios and the probability associated with each scenario p_m [19].

Stage 1

Maximise

$$\Phi(Q_n, Z | Q_r(m), y_r(m), d(m)) = -C_z Z - (C_h + C_{an}) Q_n + \mathbb{Q}(q_n, q_r | Q_n, Z) \tag{9}$$

Subject to

$$Q_n, Z \geq 0 \tag{10}$$

Stage 2

Maximize

$$\mathbb{Q}(q_n, q_r | Q_n, Z) = E_m \phi(Q_n, Z; m) = v_n q_n + v_r q_r \tag{11}$$

Subject to

$$q_n \leq Q_n \tag{12}$$

$$q_r \leq y_r(m) Q_r(m) \quad m \in M \tag{13}$$

$$q_n + q_r \leq d(m) \quad m \in M \tag{14}$$

In less capacity intensive case

$$q_n + \alpha q_r \leq Z \tag{15}$$

In more capacity intensive case

$$q_n + \gamma^{-1} q_r \leq Z \tag{16}$$

$$q_n, q_r \geq 0 \tag{17}$$

In the first stage, the problem is solved as a deterministic equivalent problem (DEP), which accounts for the uncertainty of demand, supply, and quality of returns. Using this DEP, the capacity and raw material inventory levels are calculated before uncertain parameters (demand, returns and their quality) are realized. Once uncertainty is realized, production decisions are determined while minimizing total costs and effectively utilizing the resources. As mentioned above, the DEP is presented as follows.

Maximise

$$\Phi(Q_n, Z | Q_r(m), y_r(m), d(m)) = -C_z Z - (C_h + C_{an}) Q_n + \sum_{m=1}^{M} p_m \left(v_n q_n^m + v_r q_r^m \right) \tag{18}$$

Subject to

$$q_n^m \quad \leq Q_n \quad \forall m \in M \tag{19}$$

$$q_r^m \leq y_r^m Q_r^m \quad \forall m \in M \tag{20}$$

$$q_n^m + q_r^m \leq d^m \quad \forall m \in M \tag{21}$$

In less capacity intensive case

$$q_n^m + \alpha q_r^m \leq Z \quad \forall m \in M \tag{22}$$

In more capacity intensive case

$$q_n^m + \gamma^{-1} q_r^m \leq Z \quad \forall m \in M \tag{23}$$

$$Z, Q_n, q_n^m, q_r^m \geq 0 \tag{24}$$

4. Numerical analysis and discussion

The primary goal of this section is to compare the less capacity intensive and more capacity intensive cases in terms of decisions. The secondary goal is to deliver intuitions by analysing in which situations manufacturing continues to be economically more viable and in which circumstances remanufacturing become more interesting. For computational tests, we presented a numerical example along with scenario-based analysis. In the scenario-based analysis, we generated 27 instances (three levels for each uncertain parameter) and discussed the results. The mathematical model was coded in the Visual Studio 2010 using CPLEX 12.5 solver with C++ API. The tests were conducted on a computer with Intel® Core(TM) i5- 4570T CPU @ 2.90 GHz, under the windows 64-bit operating system with 12 GB RAM.

4.1 *Numerical example*

In this section, the model is examined for optimal policy at given parameters for both less and more capacity intensive cases.

4.1a *Data*: For all our experimental analysis, an example with five scenarios is considered with high mix uncertainty. For concreteness, the data is generated from the literature. The choice of parameter values for the numerical study is largely derived from [14, 18, 19]. The demand at the primary market and the amount of core returns are presented in Table 1, along with corresponding yields and probabilities in each scenario. The capacity investment cost for one unit is taken as $10, and the unit procurement cost for raw material and used products is $15 and $25 respectively. Next, the raw material and core returns are processed at the expense of $20 and $10 per unit respectively, at the production facility. Once produced, the new products are sold at a rate of $100 per unit in primary market and reman products are sold at a discounted price of $90 per unit in secondary market, respectively. After demand fulfillment, the excess amount of raw materials is held at the cost of $10 per unit per period and returns are disposed at the cost of $2 per unit. The firm is penalized with $10 per unit if the demand is not satisfied due to lack of supply or maintenance.

Table 1. Demand, yield, and probability for each scenario.

Scenario	Demand	Core returns	Yield - returns	Probability
1	447	265	0.78	0.10
2	583	125	0.73	0.25
3	601	333	0.75	0.30
4	534	186	0.79	0.2
5	497	221	0.76	0.15

4.1b *Computational results*: The relative capacity of remanufacturing over manufacturing (α) and the relative capacity of manufacturing over remanufacturing (γ) are taken as 0.9 and 0.9, respectively. At the beginning of the period, the demand at the primary market (d) is realized as 647 units, and core returns (Q_r) is observed as 285 units. The firm found that 19% of core returns have a poor quality which can't be used further for remanufacturing. The optimal policy that is seen by solving two-stage stochastic linear program is presented in Table 2 for both less and more capacity intensive cases.

From results, as expected, the capacity installed is higher in the more capacity intensive case than the less capacity intensive case and unchanged in raw material procurement. However, it is observed that the production quantities are varied in both cases. In less capacity intensive case, the capacity primarily used to produce remanufactured products whereas the capacity used primarily to produce new products in the more capacity intensive case. The profit of the firm is a little higher in the less capacity intensive case compared with, the more capacity intensive case.

4.1c *Scenario-based analysis*: i *Data and scenarios generation*

In this section, a scenario-based approach is presented for solving the stochastic problem and analyzed results. Several researchers [20–24] discussed the importance and applicability of scenario-generation methods for stochastic programming models. Hence, the study is carried out by considering three realizations for each uncertain parameter (Good (G), Fair (F), Bad (B) for core returns yield and High (H), Medium (M), Low (L) for other uncertain parameters) (Figure 2). By combining them a total of 27 (= 3^3) scenarios are generated as shown in Table 3. For example, instance three states low core returns supply, high product demand and bad yield of core returns. Further, the data for uncertain parameters in each scenario is presented in Table 4.

ii *Results*

The instances mentioned above are solved for optimality in both less and more capacity intensive cases. The average results, which include resources utilization and service level, are presented in Table 5. For example, for instance 11, the capacity is utilized 94% in the less capacity intensive case whereas only 82.4% capacity utilized in more capacity intensive case.

Furthermore, we compared the core returns utilization in both less and more capacity intensive cases and represented in Figure 3. From Figure 3, it should be noted that the core returns utilization is higher in the less capacity intensive case than the more capacity intensive case for all instances. Also, it is observed that the core returns utilization is decreasing with a decrease in core returns quality not surprisingly. The difference in core returns utilization between less and more capacity intensive cases is increases with a decrease in demand. Hence, the profit is high in the less capacity intensive case than the more capacity intensive case. Figure 4 represents the comparison of different

Table 2. Optimal policy for numerical example in both less and more capacity intensive cases.

Case	Stage—1			Stage—2		
	Z^*	Q_n^*	*Profit*	q_n^*	q_r^*	*Profit*
Less capacity intensive	590 units	492 units	\$24820	382 units	231 units	\$27110
More capacity intensive	613 units	492 units	\$24589	492 units	109 units	\$26636

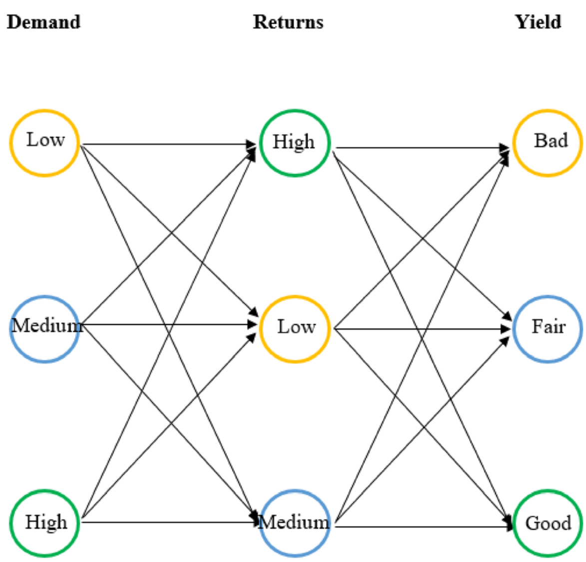

Figure 2. Scenarios structure.

objective function (profit) values for both less and more capacity intensive cases.

Assessing the results further, following significant conclusions are made:

- It is found that the raw material procurement is influenced by the amount and yield of used products, and they are inversely proportional to each other in both less and more capacity intensive cases.
- The production quantity of new products is decreased when the demand level changes from high to medium and medium to low. Also, it important note that, when returned products have good quality, the production quantity of new products is less compared to the case where returned products have fair quality and then bad quality.
- High service level is achieved for instances having medium demand (99.3 %) in the less capacity intensive case and for instances having high demand (100 %) in more capacity intensive case. In contrast to this, there exists a shortage of resources for instances having low demand in both cases.
- The core returns are utilized extremely in case of M – H – G (i.e. medium demand, high amount of returns and good yield) and slightly in case of M – L – B (i.e. medium demand, low amount of returns and bad yield).
- The procured raw material is utilized fully in all the instances except those instances have low demand in both less and more capacity intensive cases.
- Interestingly it found that the capacity utilization rate is high in the less capacity intensive case

Table 3. Scenarios generation.

Instance no	Demand	Returns	Yield	Instance No	Demand	Returns	Yield
1	H	L	G	15	M	M	B
2	H	L	F	16	M	H	G
3	H	L	B	17	M	H	F
4	H	M	G	18	M	H	B
5	H	M	F	19	L	L	G
6	H	M	B	20	L	L	F
7	H	H	G	21	L	L	B
8	H	H	F	22	L	M	G
9	H	H	B	23	L	M	F
10	M	L	G	24	L	M	B
11	M	L	F	25	L	H	G
12	M	L	B	26	L	H	F
13	M	M	G	27	L	H	B
14	M	M	F				

Table 4. Data for the uncertain parameters in each scenario.

Parameter	Description	Scenarios
d^s	Product demand in scenario 's'	L: U[1,250] M: U[251,550] H: U[551,800]
Q_r^s	Core returns inventory in scenario 's'	L: U[0.30,0.40]d^s M: U[0.41,0.50]d^s H: U[0.51,0.60]d^s
y_r^s	Yield of core returns in scenario 's'	B: U(0.61,0.67) F: U(0.68,0.77) G: U(0.78,0.85)

Table 5. Utilization and service levels for instances in both cases.

	Less capacity intensive case			More capacity intensive case		
	Resource utilization			Resource utilization		
Instance no	Raw material	Capacity	Service level (%)	Raw material	Capacity	Service level (%)
1	100.0	92.3	98.6	100.0	91.3	100.0
2	100.0	93.1	98.4	100.0	91.3	100.0
3	100.0	94.2	98.1	100.0	91.2	99.9
4	100.0	93.9	98.2	100.0	91.3	99.9
5	100.0	94.6	98.0	100.0	91.4	100.0
6	100.0	95.6	97.8	100.0	91.1	99.8
7	100.0	89.2	99.5	100.0	91.4	100.0
8	100.0	91.5	98.9	100.0	91.4	100.0
9	100.0	91.5	98.8	100.0	91.5	100.0
10	100.0	94.1	99.2	100.0	82.2	99.3
11	100.0	94.0	99.2	98.1	82.4	99.2
12	100.0	94.3	99.4	97.4	83.8	98.7
13	99.3	94.1	99.5	100.0	81.3	99.7
14	99.3	94.1	99.5	100.0	81.5	99.6
15	99.7	94.2	99.6	100.0	83.2	98.9
16	99.6	93.7	99.1	100.0	80.6	100.0
17	99.7	93.7	99.1	100.0	80.5	100.0
18	99.9	94.0	99.3	100.0	82.3	99.2
19	80.5	75.5	95.4	69.1	54.9	92.8
20	80.3	76.1	95.0	68.6	55.6	92.7
21	80.0	76.0	95.0	68.3	56.7	92.1
22	80.6	71.9	97.8	70.8	52.3	93.7
23	80.6	73.0	96.9	70.2	53.1	93.4
24	80.1	73.8	96.5	69.9	54.4	92.6
25	82.0	75.4	95.5	73.9	48.9	94.7
26	81.6	76.1	95.1	72.3	50.1	94.5
27	81.0	76.2	94.8	71.6	51.3	93.5

compared with more capacity intensive case for all instances. Also, observed that the capacity utilization increases with a decrease in returns quality and decreases with a decrease in product demand.

- From results, the best and worst scenarios are observed as H – L - G with the highest profit (i.e. high demand, low amount of returns and good yield) and L – H – B with the lowest profit (i.e. low demand, high amount of returns and bad yield) respectively in both cases.

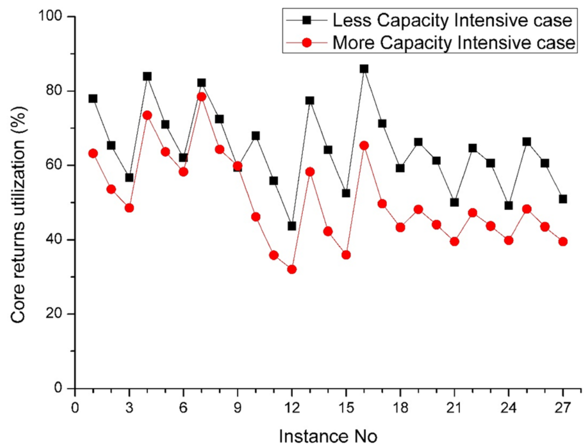

Figure 3. Core returns utilization in both less and more capacity intensive cases.

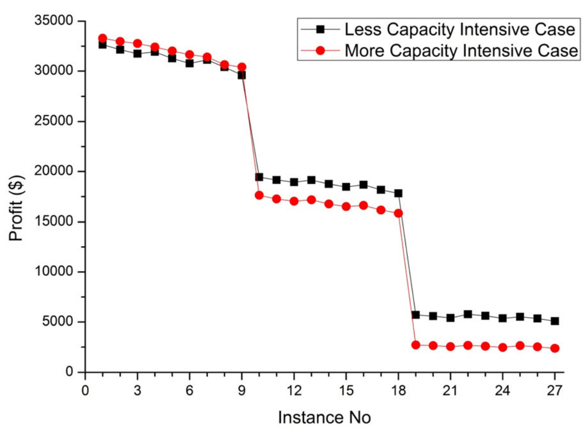

Figure 4. Objective function values comparison for both less and more capacity intensive cases.

5. Conclusion

In this paper, we have developed a stochastic model for a hybrid manufacturing - remanufacturing system to address issues of capacity, inventory, and production decisions for a firm that produces new and reman products. To impose real-life problems, uncertainty in demand, returns amount, and yield is flexibly considered in the model and the model becomes more complex. However, the model effectively balances the supply and demand rates by estimating the right capacity and raw material inventory levels. Besides, the impact of relative capacity of remanufacturing over manufacturing is analyzed via two cases, namely: less capacity intensive case and more capacity intensive case. Further, the scenario-based approach is presented with three levels for each uncertain parameter, and average results such as resource utilization and service level are presented for each possible scenario.

The results indicate that the net value associated with products can be decisive in choosing manufacturing or remanufacturing. For instance, when the net value associated with the remanufactured product is more than the new product and the core returns inventory lies between capacity level and demand, pure remanufacturing occurs and will be perfectly substituted for manufacturing. Also, it is observed that the remanufacturing process can most depend on the yield of returns, even core returns are available. Further, the instances are providing higher profit and more capacity utilization in the less capacity intensive case compared with the more capacity intensive case. Current research can be extended by considering the timing of returns with the help of the product life cycle of original products. As future work, industrial case studies can be conducted to validate the model and methodology. In future work, we can also consider carbon policies to collect and process returns.

Abbreviations

Input parameters

M	Number of scenarios
α	Relative capacity required for remanufacturing over manufacturing
γ	Relative capacity required for manufacturing over remanufacturing
C_Z	Unit capacity investment cost ($)
C_h	Unit inventory holding cost ($)
C_w	Unit disposal cost ($)
C_{an}	Unit raw materials purchasing cost per unit ($)
C_{ar}	Unit returns acquiring cost per unit ($)
C_n	Unit processing cost of new product ($)
C_r	Unit processing cost of reman product ($)
C_{sp}	Shortage penalty cost for new product per unit ($)
v_n	Net value associated with the new product ($)
v_r	Net value associated with reman product ($)
p_n	Unit selling price of new product ($)
p_r	Unit selling price of reman product ($)
p_m	Probability associated with each scenario

Uncertain parameters

d	Product demand (units)
Q_r	Core returns inventory level (units)
y_r	Yield of core returns

Decision variables

Q_n	Raw material inventory level (units)
Z	Production capacity level (units)
q_n	Optimal manufacturing quantity (units)
q_r	Optimal remanufacturing quantity (units

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