Strategic design for inventory and production planning in closed-loop hybrid systems

1. Navin K. Dev*
Department of Mechanical Engineering,
Dayalbagh Educational Institute,
Dayalbagh, Agra, INDIA
Email: navinkumardev@yahoo.com

2. Ravi Shankar
Department of Management Studies,
Indian Institute of Technology Delhi,
New Delhi, INDIA
Email: r.s.research@gmail.com

3. Alok Choudhary
Department of Management Science and Operations Management,
School of Business and Economics
Loughborough University, Leicestershire, UK
Email: A.Choudhary@lboro.ac.uk

* Corresponding Author, Email: navinkumardev@yahoo.com
Tel. No. 09412425551

Highlights (for review)

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- A closed-loop system with both manufacturing and remanufacturing is considered.
- Studied inventory and production planning models for continuous and periodic review.
- Total inventory costs and production order variance are performance indicators.
- Total inventory cost shows trade-off among demand, lead times, and review periods.
- Remanufacturing shows its contribution to low order variance in periodic review.

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Abstract

This research studies inventory and production planning in a closed-loop system while considering both manufacturing and remanufacturing. We studied five inventory and production planning models under the continuous and periodic review systems using a discrete event simulation. Under the above review policies, different demand and return rates, as well as manufacturing and remanufacturing lead times, are considered. The total recoverable and serviceable inventory costs and production order variance are considered as the main performance indicators. From the total inventory cost viewpoint, our findings reveal the trade-off between stochastic demand, stochastic lead times, and review periods. It was found that the periodic review system outperforms the continuous review system for higher values of the review period and return to demand rate ratio. Furthermore, remanufacturing demonstrates an appreciable contribution to low order variance in periodic review systems for high values of return to demand ratio and lead times.

Key words: closed-loop hybrid systems, inventory and production planning, remanufacturing, simulation, order variance

1. Introduction

Environmental consciousness about spiraling product variety and shorter life cycle are motivating the firms to reassess how to convalesce the products reaching the end of their economic lives. In the past, manufacturing companies had limited concern for how their sold products were disposed of, due to insufficient regulations and/or public awareness. Today, the companies that actively implement value recovery practices beyond the regulatory and legislation pressures can gain an organizational competitive advantage and a strong corporate environment image (Sarkis, 2012). The various means of material recovery systems involves reusing, repairing, refurbishing, remanufacturing and cannibalization (Oh and Hwang, 2006). In reusing, no components or materials are replaced and the products are reused without any alterations. Repairing involves correcting or replacing the parts in the product, which is slightly damaged. Typically, remanufacturing is different from repair operations. The products are dissembled completely, and usable parts are cleaned, refurbished and put into a serviceable inventory. Then, the new product is reassembled from the old one and returned to like-new condition (Lund 1983, Guide 2000, Oh and Hwang 2006). Recycling is a series of activities through which abandoned materials are collected, sorted, processed and used in the production of new products. Refurbishing brings used products up to specified quality, but the quality standards are lower than those for new products (Thieery et al., 1995).

The recovery process can be profitable if delivers parts which are essentially as good as new. Remanufacturing is the only process where used products are potentially brought at least to the performance specification of the original equipment manufacturer (OEM) (King et al., 2006). Products that are remanufactured currently include automobile parts, computers, aviation equipment, medical instruments, telephone equipment, machine tools, and others (Lund, 1984, Van der Laan, 1997, Guide et al., 2000). A number of companies, including Dell, General Motors, Hewlett-Packard (HP), IBM, Kodak, and Xerox, among others, have adopted remanufacturing in different ways (Deutsch 1998, Ginsburg 2001). About 90% of Kodak's one-time use cameras are produced from recycled camera bodies, and about 90% (by weight) of a used Kodak body is directly reused in the manufacture of new cameras (Mukhopadhyay and Ma 2009). Remanufacturing is a significant part of sustainable supply chain and reverse logistics. It is also pertinent to note that remanufacturing of components or sub-components (added value recovery) in a closed-loop system is much more efficient than recycling (material recovery operation) both environmentally and economically (Corum et al., 2014).

Remanufacturing is an interesting issue from an inventory and production planning (I&PP) point of view. In I&PP systems, there are two means via which the stock of serviceable items are increases: manufacturing and remanufacturing. When the product has not reached the end of its life-cycle, typically, since the rate of demand is higher than returns, both means are used. An illustration of such a hybrid system is shown in Figure 1.

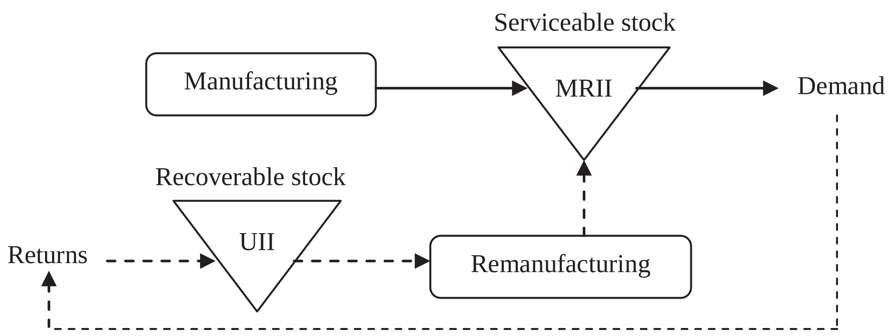


Figure 1: Hybrid inventory system with manufacturing and remanufacturing systems (Akçali and Çetinkaya 2011)

The hybrid inventory system shown in Figure 1 has been widely studied (Teunter et al. 2006, van der Laan and Teunter 2006, Zanoni et al. 2006, Konstantaras and Papachristos 2008, Pan et al. 2008, Behret and Korugan 2009, Corum et al. 2014). In the hybrid system, there are two stock points, one for the used items inventory (UII), i.e. the recoverable stock with minor damage, and one for the manufactured and remanufactured items inventory (MRII) i.e. the serviceable stock. The assumptions regarding the hybrid system are outlined as follows.

- *The remanufacturing process*. It is assumed that all collected items from customers come back to the recoverable stock inventory area (i.e. disposals do not occur) with a stochastic return rate. The remanufacturing process is initiated based on the various control policies mentioned in Section 3.1 ahead. The remanufacturing process is assumed to have unlimited capacity. After remanufacturing, the products are sent to serviceable stock, i.e. MRII, as remanufactured products. These remanufactured products are considered to be as good as regular manufactured products.

- *The manufacturing process*. Products are regularly manufactured with raw materials procured from suppliers and, for simplicity, we assume that raw materials are available all the time, i.e. no raw material inventory is kept. We assume the manufacturing capacity is unlimited. The manufacturing process is initiated based on the various control policies mentioned in Section 3.1 ahead. Both manufacturing and remanufacturing replenish the MRII from where the demand is satisfied.

Akçali and Çetinkaya (2011) have comprehensively reviewed the literature on I&PP models in the closed-loop supply chain. They have discussed the variants of the basic system shown in Figure 1. In the present research, we have studied the continuous and periodic review policies illustrated by Akçali and Çetinkaya (2011) from the viewpoint of the basic structure of the hybrid model exhibited in Figure 1. The five cases of the model are discussed in Section 3 ahead.

The present research addresses two issues of I&PP related to parameters, namely, the stochastic demand and return rates, stochastic manufacturing and remanufacturing processing time, manufacturing and remanufacturing set-up costs, and inventory holding rates. The associated performance evaluated is *total inventory cost*. Secondly, manufacturing ordering variances are calculated, and the bullwhip effect is discussed within the hybrid manufacturing and remanufacturing system. The associated performance determined is *production order variance*. These two performances are commonly used in the literature since one of the potential problems of hybrid systems related to inventory management of recoverable products include the amount of inventory to hold and the time to manufacture and remanufacture. Some of the researches include (Zhou and Disney 2006, Zanoni et al. 2006, Behret and Korugan 2009, Corum et al. 2014).

This paper is structured as follows. In Section 2 we survey the literature and outlined our research contributions. Section 3 demonstrates the five cases of hybrid production system defined within I&PP policies. In Section 4, details of the simulation model are provided. Section 5 discusses the findings of the study while the paper concludes with final observations in Section 6.

2. Literature review

In the recent times, the enhanced level of responsiveness due to mass customization has become a key factor in manufacturers becoming competitive. Furthermore, in a world of finite resources and disposal capacities, the recovery of used products and materials has become an endemic concern in industrialized countries. As a result, many countries have started to emphasize the prevention and control of pollution caused by discarded wastes. Regulations and laws have been established to restrict and regulate the procedure for the return and recycle of these hazardous wastes. The European Union has established stricter codes for the handling of products containing hazardous substances, such as Directive 2002/96/EC related to 'Waste Electrical and Electronic Equipment' (WEEE), Directive 2002/525/EC related to End of Life and the 'Restriction of the use of certain Hazardous Substances in electrical and electronic equipment' (RoHS) regulations. The concept of material cycles is gradually replacing a 'one-way' perception of the economy. Increasingly, customers expect companies to minimize the environmental impact of their products and processes.

Take-back and recovery obligations have been enacted or are underway for a number of product categories including electronic equipment in the European Union and in Japan, cars in the European Union and in Taiwan, and packaging material in Germany. In this vein, the past two decades have witnessed an immense growth in product recovery activities. Some of the enterprises that are putting substantial efforts into remanufacturing used equipment include copy machine manufacturers Xerox and Canon. Xerox conducted resource recycling for collected products at a rate of 99.9 percent in 2011. They also reduced new resources use by 2,272 tons. The main drivers behind this achievement are the increase in both products containing reused parts and the amount of resources recycled from consumable cartridges (Fuji Xerox, Sustainability Report, 2012, p. 23 (refer 46)). Canon has been operating two remanufacturing factories for used copy machines in Virginia (USA) and in the UK since 1993 and is currently exploring comprehensive recycling systems for all copier parts. Toner cartridges have been collected for reuse since 1990 and have recycled around 287,000 tons of cartridges had been recycled by the end of 2011, thereby saving around 430,000 of CO_2 (Canon Europe Sustainability Report 2011-2012, p. 5 (refer (47)). Yet another example of product recovery concerns single-use cameras. Kodak started in 1990 to take back, reuse and recycle its single-use cameras, which had originally been designed as disposables. When manufacturing new cameras, Kodak uses 86 percent reused parts (David and Stewart, 2008). Some companies use remanufacturing of obsolete product components as a strategy for upgrading products (e.g., HP's mainframe systems (Kupér, 2003) and Nortel's network systems (Linton and Johnston, 2000)). Another group of companies recovers the parts and components from used products to provide remanufactured replacement parts for customer service support, a process known as cannibalization of components (e.g., IBM's computer service parts (Fleischmann *et al*., 2004)). Lastly, a number of companies collect their used products for material recovery to provide recycled materials to support their own operations or sell to other industries (Guide and Van Wassenhove, 2003), for example, the plastic components recycling programs implemented by HP for printer cartridges and by Dell for computer peripherals.

Accordingly, we find that the contemporary business environment necessitates the manufacturers to concurrently focus on the responsiveness as well as the sustainability initiatives. The inventory management concerning recoverable products has been the subject of considerable research efforts since the 1960s (Mitra 2007). The literature concerning five I&PP models of closed-loop supply chain considered in the present research has comprehensively been discussed by Akçali and Çetinkaya (2011). Inventory management in hybrid systems has received significant interest since the first model by Simpson (1978). He made an explicit attempt to develop an integrated inventory policy. He considered a repairable inventory problem with two stocking points, i.e., serviceable and repairable inventories. Later van der Laan and Salomon (1997) developed two continuous review policies referred to as push-disposal and pull-disposal. While the push-disposal policy considered the returned products to enter the remanufacturing process as soon as the remanufacturable inventory reached a certain level, in pull-disposal policy, the returned products are remanufactured depending on the levels of both serviceable and remanufacturable inventories. Teunter and Vlachos (2002), through a simulation analysis, identified the conditions under which the disposal of the returned products can be beneficial. They suggested that a considerable cost reduction can be obtained under low demand rate.

Information distortion, which is popularly known as the bullwhip effect, refers to the phenomenon where orders to the supplier tend to have a larger variance than sales to the buyer. This distortion propagates upstream in an amplified form (Lee et al. 1997). Souza et al. (2002) examined production planning and control for a remanufacturing based on the queuing network. They analyzed the analytical models for optimal product mix while maintaining the desired service level in terms of flow times. Furthermore, they examined the remanufacturing model through simulation for three dispatching rules; Random, MaxDiff, and Dynamic, based on the flow time with different processing time due to differing quality grades of returns. Zhou and Disney (2006) found that inventory variance and thus bullwhip effect are always lower in supply chains with returns than without returns. Zanoni et al. (2006) analyzed the problem of the inventory system within the hybrid system by introducing a shifted pull inventory control policy. They compared the shifted pull inventory control policy with pull, dual, and separate pull-control policies previously studied in the literature. They stated that with significantly longer manufacturing lead time than the remanufacturing, pull policy in remanufacturing and dual policy in manufacturing reduce the bullwhip effect, and that both the policies perform better for the total inventory cost than the other policies. Behret and Korugan (2009) analyzed remanufacturing operations from a quality level of returns perspective. They assumed that a low level of returns quality requires more remanufacturing efforts. They suggested that quality-based classification of returned products yields significant cost savings. Lund and Hauser (2010) appraised the benefits of environmentally conscious remanufacturing and its implications. Ilgin and Gupta (2010) observed that remanufacturing involves the accurate estimation of product returns, production planning and scheduling, capacity planning, and inventory management. El Saadany et al. (2013) developed a mathematical model to estimate the number of recovery times. They stated that there exist an optimal number of remanufacturing generations that balances investment and remanufacturing costs.

A recent research work which deals with a similar issue to those addressed in the present study was conducted by Corum et al. (2014). For a hybrid manufacturing and remanufacturing system similar to the structure is shown in Figure 1, Corum et al. (2014) compared push-and-pull-controlled hybrid production system with the traditional one. The total inventory cost, and manufacturing and remanufacturing order variance, are considered as the performance measures. The impact of various inventory related parameters was studied through simulation. While the pull strategy considered in Corum et al. (2014) is similar to Case 1 presented in the present research, the push strategy is partly similar to Case 4 of the present research, i.e., all available returns are remanufactured to replenish the serviceable inventory. However, Corum et al. (2014) confined their study to continuous review policy. In contrast, our study addresses the issue of comparing continuous review policy with the periodic review policy system for five different cases. These cases are described in the next section. Corum et al. (2014) suggested studying periodic review policies. Thus, the present research is an extension of their efforts.

With the above objectives in mind, we foresee that the present research provides a sound and insightful basis for exploring closed-loop systems with manufacturing and remanufacturing processes under the purview of I&PP.

3. System description

In this study, the five I&PP models are compared. It is assumed that a manufacturer produces a single product, and controls the production quantity according to two inventory review policies continuous and periodic.

In continuous review policy, the system follows (r, Q) policy, i.e., the inventory is monitored continuously and an order for production quantity equal to Q is generated when the inventory level is less than, or equal to, reorder point r. In periodic review policy, upon review in period t, the order for production quantity equal to manufacture order-up-to level (R_m) and in the case of remanufacturing the order is equal to remanufacture order-up-to level (R_r) which is generated under different conditions of manufacturing and remanufacturing I&PP control policies. The lead times for manufacturing (L_m) and remanufacturing (L_r) are normally distributed. The control strategies of continuous and periodic manufacturing and remanufacturing are shown in Figure 2(a) and 2(b) respectively.

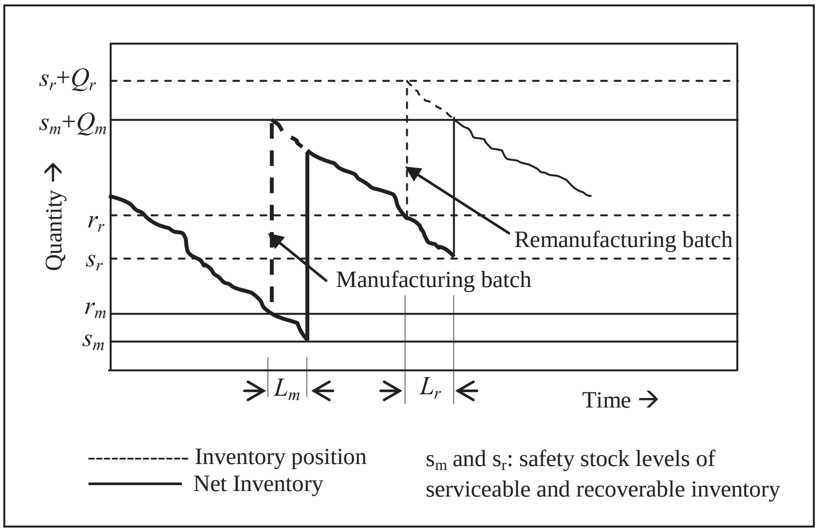


Figure 2(a): Hybrid system under continuous review policy

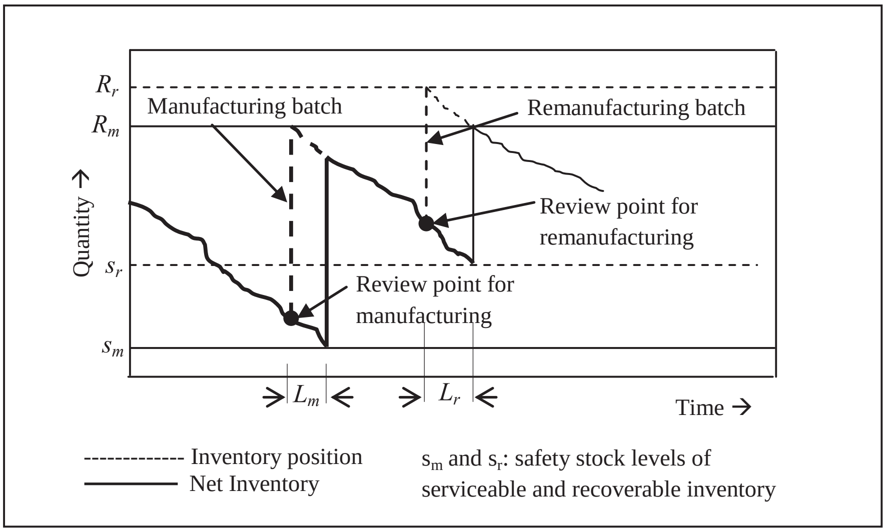


Figure 2(b): Hybrid system under periodic review policy

In the hybrid manufacturing and remanufacturing systems, the items from the customers are collected for the recoverable inventory area. They are remanufactured based on five I&PP control policies discussed later in this section. Then, they are sent to the serviceable stock from where the customer demand is satisfied. The five I&PP control policies operating under two review policies; continuous and periodic are discussed as follows.

3.1 Notations and cases

Notations

r_r	remanufacturing reorder level
r_m	manufacturing reorder level
q_r	remanufacturing order quantity
q_m	manufacturing order quantity
R_r	Remanufacturing up-to level

R_m Manufacturing up-to level

$IP_u(t)$ number of parts in UII at time t

$IP_{mr}(t)$ number of parts in MRII at time t

Continuous review policy:

Case 1: (r_r, q_r, q_m) policy – This policy is characterized by r_r, q_r, and q_m.

if

$IP_{mr}(t) = r_r$ and $IP_u(t) \geq q_r$;

Remanufacturing of batch q_r is released to replenish MRII by UII.

Else

if

$IP_{mr}(t) = r_m$;

Manufacturing of batch q_m is released to replenish MRII.

Note that under this policy remanufacturing is given priority over manufacturing i.e., $r_m < r_r$.

Case 2: (r_r, R_r, r_m, q_m) policy – This policy is characterized by r_r, R_r, r_m, and q_m.

if

$IP_{mr}(t) = r_r$ and $IP_u(t) = R_r - r_r$;

Remanufacturing batch of size $(R_r - r_r)$ is released to replenish the MRII.

Else

if

$IP_{mr}(t) = r_m$;

Manufacturing of batch q_m is released to replenish MRII.

Again under this policy remanufacturing is prioritized over manufacturing i.e., $r_m < r_r$.

Periodic review policy:

Case 3: (R^t_m, R^t_r) policy – This policy is characterized by R^t_m and R^t_r. The superscript t represents the beginning of period. Upon review in period t,

if

$IP^t_{mr} + IP^t_u < R^t_m$;

A batch of size ($R^t_m - (IP^t_{mr} + IP^t_u$) for manufacturing and a remanufacturing batch of size IP^t_u are released to replenish the MRII.

Else

if

$R^t_m \leq IP^t_{mr} + IP^t_u < R^t_r$;

A remanufacturing batch of size IP^t_u is released to replenish the MRII.

Under this policy remanufacturing is prioritized over manufacturing i.e., $R^t_m \leq R^t_r$.

Case 4: (R^t_m) policy – This policy is characterized by a single manufacturing up-to level R^t_m. In each period, a remanufacturing batch of size IP^t_u is released, i.e., all available returns are remanufactured to replenish the MRII. After the remanufacturing decision is made,

if

$IP^t_{mr} < R_m$;

A manufacturing of batch size ($R_m - IP^t_{mr}$) is also released to replenish MRII.

Case 5: (R_m, R_r) policy – This policy is characterized by R_m and R_r. There are two different realizations of this policy.

(i) The first execution prioritizes the manufacturing, i.e., upon review in period t,

if

$IP^t_{mr} < R_m$;

A manufacturing batch of size (R_m – IP^t_{mr}) is released to replenish MRII. After the manufacturing batch is released,

if

$IP^t_{mr} < R_r$;

A remanufacturing batch of size min{IP^t_u, R_r – IP^t_{mr}} is also released. This policy is denoted by Type-1 policy of Case 5.

(ii) The second execution prioritizes the remanufacturing, i.e., upon review in period t,

if

$IP^t_{mr} < R_r$;

A remanufacturing batch of size min{IP^t_u, R_r – IP^t_{mr}}is released to replenish MRII. After the remanufacturing batch is released,

if

$IP^t_{mr} < R_m$;

A manufacturing batch of size (R_m – IP^t_{mr}) is released. This policy is denoted by Type-2 policy of Case 5.

4. The simulation model description

Simulation is among the most commonly used techniques to study the impact of different factors on the performance of a reverse or closed-loop supply chain (Ilgin and Gupta 2010). In a thorough and recent literature review conducted by Agrawal et al. (2015), the authors mentioned that there are very few simulation models, which have been developed for reverse logistics network design. Guan and McKay (2014) conducted simulation experiments to study the priorities, issues, and challenges concerning sustainability in the Malaysian palm oil industry.

They linked different tiers in the supply chain network through information so as to study the behavior of different entities and their interactions in the plantation, mill and mill-refinery models. Kumar and Rehman (2014) reported the application of an RFID-enabled process reengineering in sustainable healthcare system design and presented a case study of a Singapore hospital using ARENA simulation. They found that RFID implementation resulted in improving the efficiency of the closed-loop supply chain. Shi et al. (2014) developed an agent-based simulation model to simulate the solid waste management system. Zolfagharinia et al. (2014) developed separate serviceable and remanufacturing inventory stock points for a reverse supply chain with stochastic return demand. The objective of remanufacturing stock point is to take advantage of low holding cost. They developed a hybrid simulation and meta-heuristic approach for an inventory control problem. Other researchers that have explored simulation modeling recently include Frantzen et al. (2011) and Saxena and Wadhwa (2009). To this end, the present paper is an attempt to develop a simulation model that integrates manufacturing with the remanufacturing set-up.

The simulation model of the hybrid manufacturing and remanufacturing system was developed in the Arena® simulation language (Kelton et al. 2010). The External Visual C++ code was linked to the Arena model to capture the inventory control logic utilized in the simulation models. In addition, since simulation in Arena® involves samples from probability distributions (e.g., for customer demand, lead times and their standard deviations etc.), it is recommended that a requisite number of replications of a sufficiently long duration (in order to eliminate the initial transient bias) be carried out in order to justify the normality assumption required for the statistical interpretation of simulation results. In our experiments, therefore, the simulation models were run for 1500 periods with 10 replications which were found adequate for analysis purposes. The first 500 periods are set as the warm-up period to eliminate the effect of initial setup by observing average serviceable inventory levels to reach a steady state. Consistent with Corum et al. (2014), the parameters and their levels used in the simulation models are listed in table 1.

Table 1: Overview of experimental factors and levels

Fixed Factors	
Demand rate (units/period)(λ_D)	EXPO(12); EXPO(8); EXPO(5)
Return rate (units/period)(λ_r)	EXPO(4)
Remanufacturing lead time N(L_r, σ_r^2)	(4,1)
Manufacturing lead time N(L_m, σ_m^2)	(2,1); (4, 1); (6, 1); (8, 1)
Remanufacturing set-up cost K_r ($/batch)	$10
Manufacturing set-up cost K_m ($/batch)	$50
Inventory holding rate (i) (%/1000 periods)	5%
Holding cost of serviceable inventory h_s ($/1000 periods/unit)	200*i
Holding cost of recoverable inventory h_r ($/1000 periods/unit)	20*i
Experimental Factors	
Review Period (periods)	4; 6; 8
Inventory policy	Continuous (r, Q); Periodic (order up-to level)
I&PP control policies	Case1 through Case 5

The impact of various parameters such as demand rate (λ_D), manufacturing lead time (L_m), remanufacturing set-up cost (K_r), and serviceable (h_s) and recoverable (h_r) holding cost rates are investigated. The demand rate (λ_D) and return rate (λ_r) are assumed to be exponentially distributed with differing parameters. Manufacturing and remanufacturing lead times are normally distributed over a small spread of one and the unsatisfied demand is lost. Similar assumptions are made in the extant literature (Mahadevan et al. 2003, Bayındır et al. 2005, Zanoni et al. 2006, Behret and Korugan, 2009).

Furthermore, consistent with Corum et al. (2014), the unit cost of the returned product, remanufactured product, and manufactured product are set to \$20, \$110 and \$200 respectively. The lot sizes, h_r is estimated as a net unit contribution of remanufacturing compared to manufacturing (\$200 – \$110 = \$90). The cost parameters considered are in line with the literature (Lund and Hauser 2010, Wu 2012, Corum et al. 2014). Remanufacturing and manufacturing lot sizes (Q_r and Q_m) are computed by a simple Economic Order Quantity (EOQ) formula, whereas reorder points r_m and r_r are calculated according to classical inventory theory models with stochastic demand and lead time. Consistent with Corum et al. (2014), the remanufacturing process is given priority and consequently, the formulae are as follows:

$$r_m = \lambda_D \times (L_m + OI) + z\sqrt{(L_m + OI) \times \lambda_D + \lambda_D^2 \times (\sigma_m)^2} \text{, and} \ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

$$r_r = \max\{\lambda_D \times (L_r + OI) + z\sqrt{(L_r + OI) \times \lambda_D + \lambda_D^2 \times (\sigma_r)^2}\ , r_m\} \ldots\ldots\ldots\ldots\ldots \text{(2)}$$

In the above equations, z represents standard normal distribution parameter for stockout risk (assumed as 5 percent in the simulation). The value of OI (order interval) depends on the review policy adopted. Since we do not consider any protection interval in continuous review policy, there is no role of OI. Thus, in the continuous review policy, the value of OI is kept negligibly small and can be neglected in the formula. Whereas, in the case of periodic review policy, the value of OI is an experimental factor and studied for three levels. The total inventory cost is studied for both manufacturing and remanufacturing processes that include total inventory holding cost plus the total setup cost for both manufacturing and remanufacturing. However, the order variance is calculated at manufacturing end to study the joint effect of manufacturing and remanufacturing for all the five cases. Along the lines of Corum et al. (2014), total inventory holding cost of recoverable items is estimated as h_r = \$20*i, where i is the inventory holding rate per 1000 period, and the unit holding cost of serviceable items as h_s = (\$110*r – \$200*(1-r))*i. It is assumed that $r = \lambda_r / \lambda_D$ percent of the serviceable items are received from remanufacturing. The total inventory cost function C(.) reads as:

$$C(.) = h_s I_s^{OH} + h_r I_r^{OH} + K_r O_r + K_m O_m \qquad \ldots\ldots\ldots\ldots\ldots (3)$$

where

I_s^{OH} = On-hand serviceable inventory.

I_r^{OH} = On-hand recoverable inventory.

O_r = Total number of ordered batches for remanufacturing per 1000 period.

O_m = Total number of ordered batches for manufacturing per 1000 period.

To calculate the production order variance (bullwhip effect) in each experiment, we use the formula as follows (Zanoni et al., 2006).

$$BW = \frac{\sigma_{OR}^2}{\sigma_D^2} \qquad \ldots\ldots\ldots\ldots\ldots (4)$$

where:

BW = Bullwhip effect at the manufacturing end.

σ_{OR}^2 = Long-term variance of orders at the manufacturing end.

σ_D^2 = Long-term variance of demand at the manufacturing end.

The demand variance (σ_D^2) within the simulation remain constant for a specific experiment e.g., for the demand per time unit (=EXPO(12)), the mean inter-arrival rate, μ is equal to 0.083 (=1/12) time units). The order variance (σ_{OR}^2) is calculated by incorporating the relation ($\frac{\sum(X-\mu)^2}{N}$) in the simulation model affected by each individual control policy studied.

where,

X = parameter related to inter-arrival rate of order entities generated for manufacturing process,

N = Number of batches ordered for manufacturing per 1000 period.

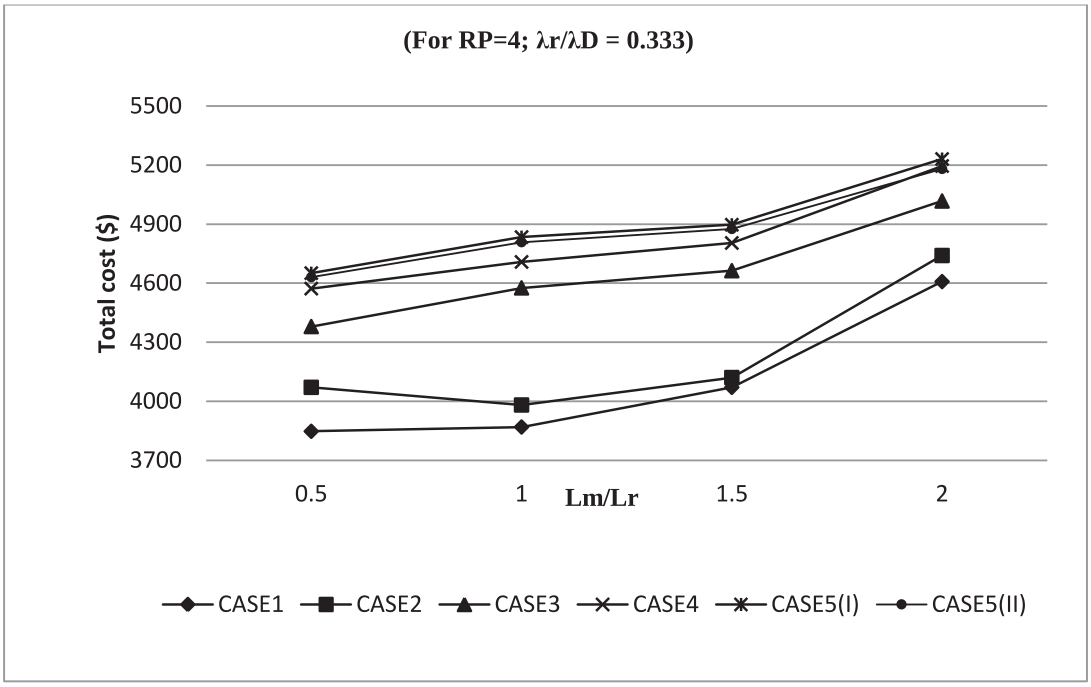
5. Results and discussions

In Figure 3 – 5, total recoverable and serviceable inventory cost for Case 1 through Case 5 of continuous review policies and periodic review policies are presented for different values of lead time ratio (L_m/L_r) and return to demand ratio (λ_r/λ_D). To begin with, first, we compare the continuous review policy cases (Case1 and Case2) with periodic review cases (Case3 through Case 5(I&II)) for total inventory cost performance.

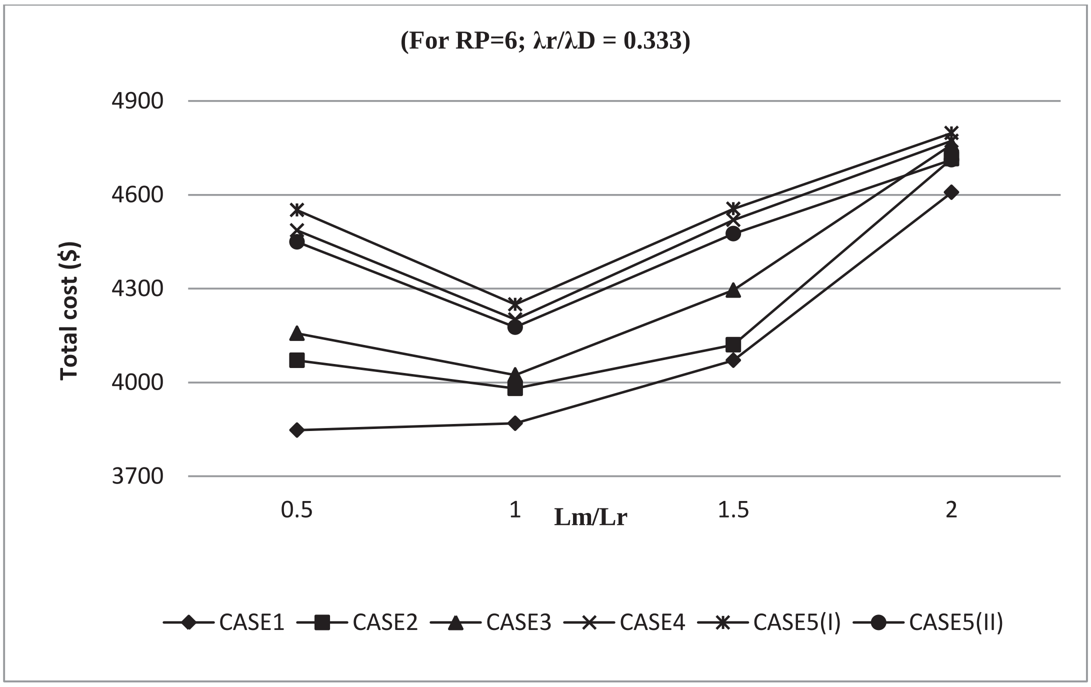
The total inventory cost for both continuous and periodic review policies increases with the higher values of manufacturing lead times (i.e., increasing values of L_m/L_r). The explanation for this is straightforward that the increasing values of manufacturing lead times causes the increase in the value of manufacturing re-order point (r_m) and also the re-order point of remanufacturing (r_r) value ($r_m \leq r_r$). However, it is seen in Figure 3 and Figure 4 that the periodic review system shows a decreasing trend in total inventory cost up to a certain value of L_m/L_r and then increases. This trend may be explained by the fact that, given the larger values of demand rate (low value of ratio λ_r/λ_D) and low processing time of manufacturing, the regular products reduce from the serviceable inventory faster, due to which the average number of regular products in the serviceable inventory queue remains low. This results in low holding cost. This trend can be seen up to larger values of L_m/L_r for increasing values of the review period. However, this decreasing trend of total inventory cost is offset by high values of λ_r/λ_D ratio, i.e., for low demand rate (Figure 5), and total inventory cost shows the increasing trend.

Interestingly, the periodic review policy system shows its potential vis-à-vis the continuous review system for total inventory cost with increasing values for the review period. This may be explained by the fact that the higher values of the review period lead to fewer orders over the total time horizon. This results in lower manufacturing set-up cost and thereby constructively affects the total inventory cost. The effectiveness of the periodic review system is further seen to contribute to the reduction of total inventory cost for higher values of return to demand ratio (i.e., λ_r/λ_D). The impact of remanufacturing due to recoverable items is appreciably seen in this result. The relative increase in recoverable items reduces the holding cost and thereby the total inventory cost at large. Such a result concerning the potential of periodic review system can also be anticipated if manufacturing set-up cost is lower than remanufacturing set-up cost for the decreasing values of λ_r/λ_D. However, the explicit value of total cost, in this case, needs further investigation which can be considered in future work. Thus, the results shown in Figure 3 through Figure 5 necessitate for the strategic adoption of review policy in a trade-off with L_m/L_r and λ_r/λ_D ratios.

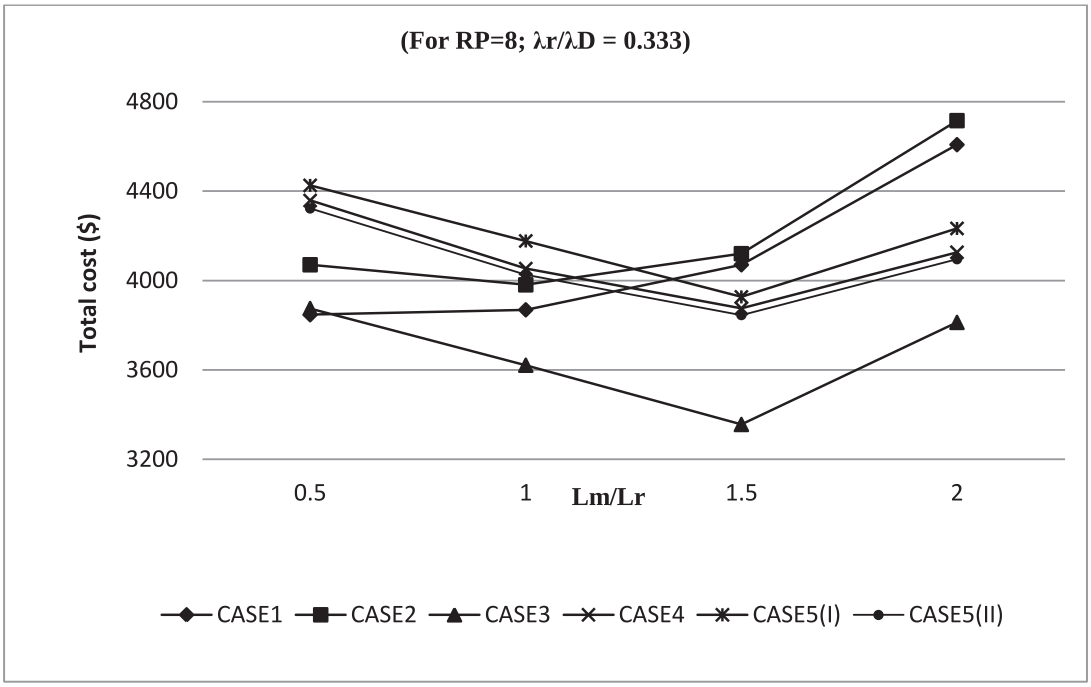
Comparing each of the periodic review case (Case3 through Case5 (I&II)), from Figure 3 through Figure 5, it is seen that Case 3 outperforms the other cases under all the specified parameters for total inventory cost. It is evident from the result that the production order should be realized by jointly considering the levels of manufactured and remanufactured inventory at the time of review.



3(a)

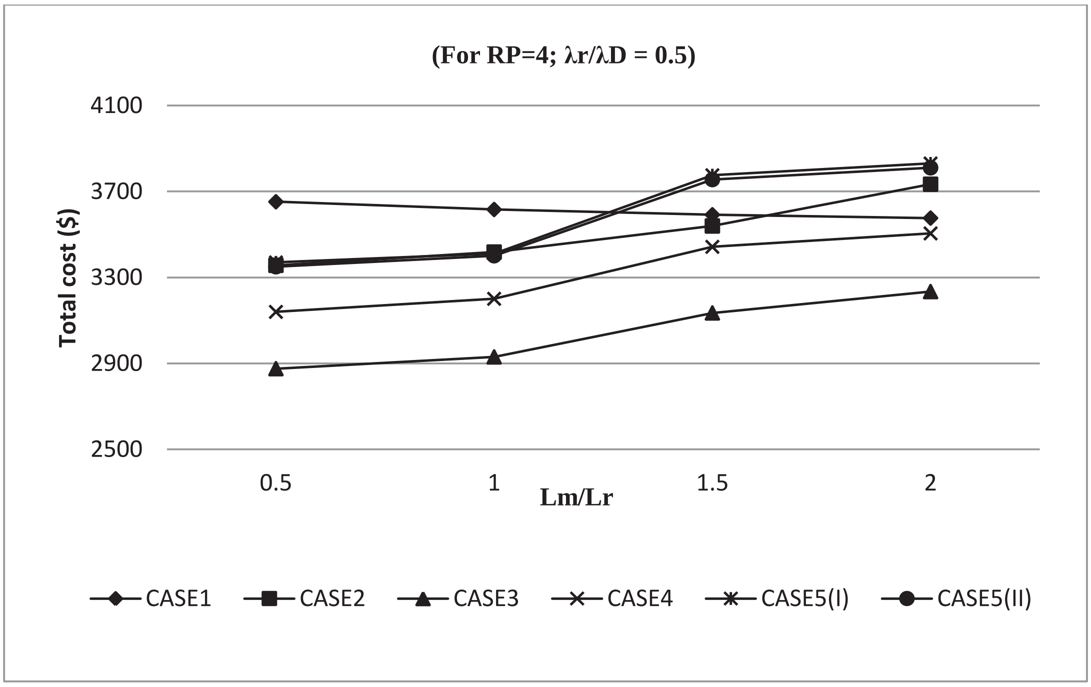


3(b)

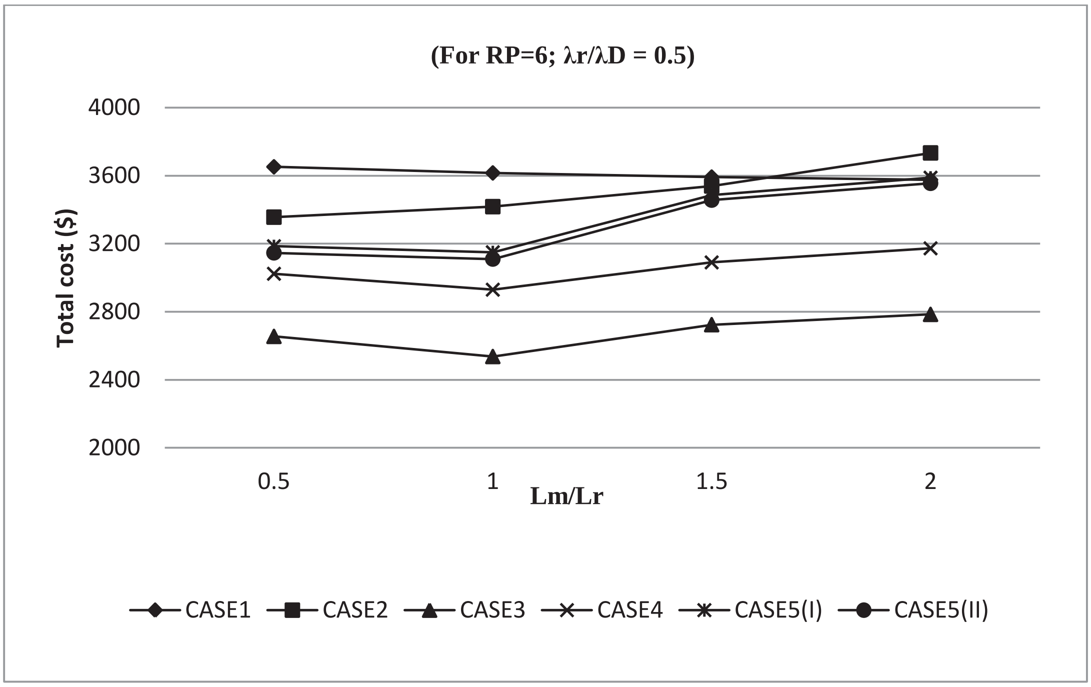


3(c)

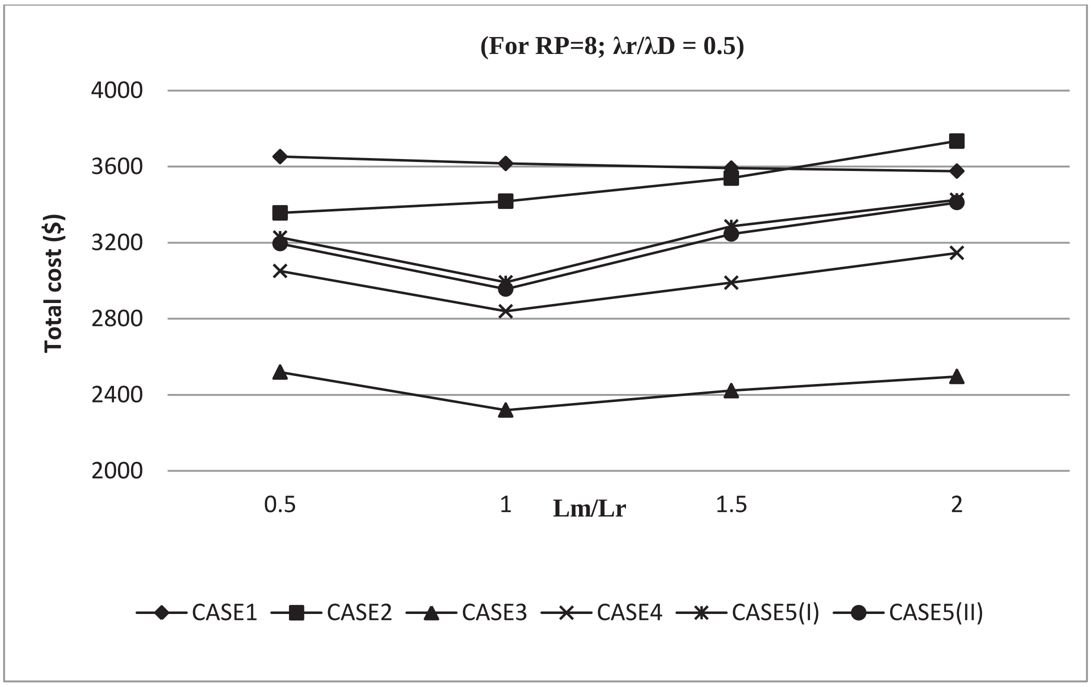
Figure 3: Total inventory cost for five cases with ((a) RP=4, (b) RP=6 and (c) RP=8; λ_r / λ_D = 0.333)



4(a)

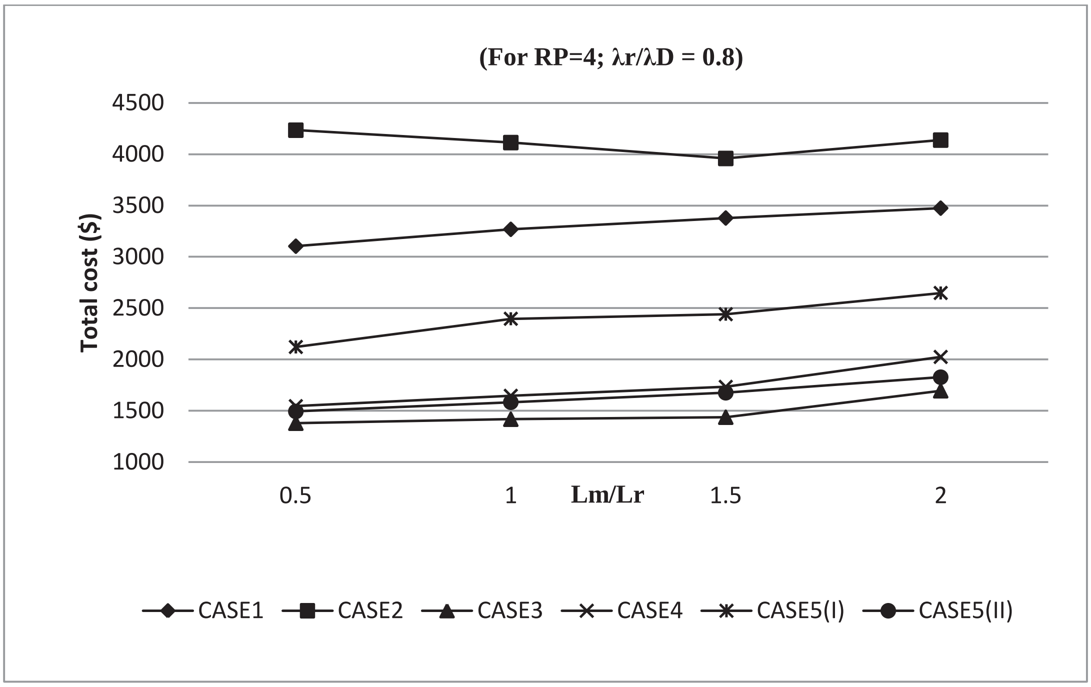


4(b)

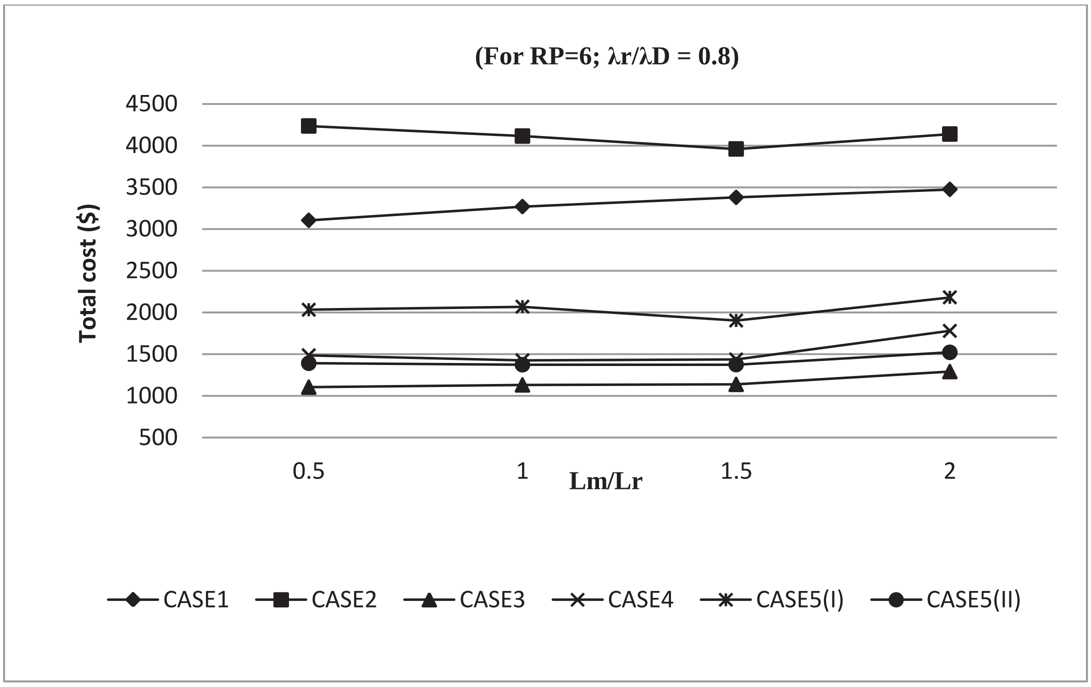


4(c)

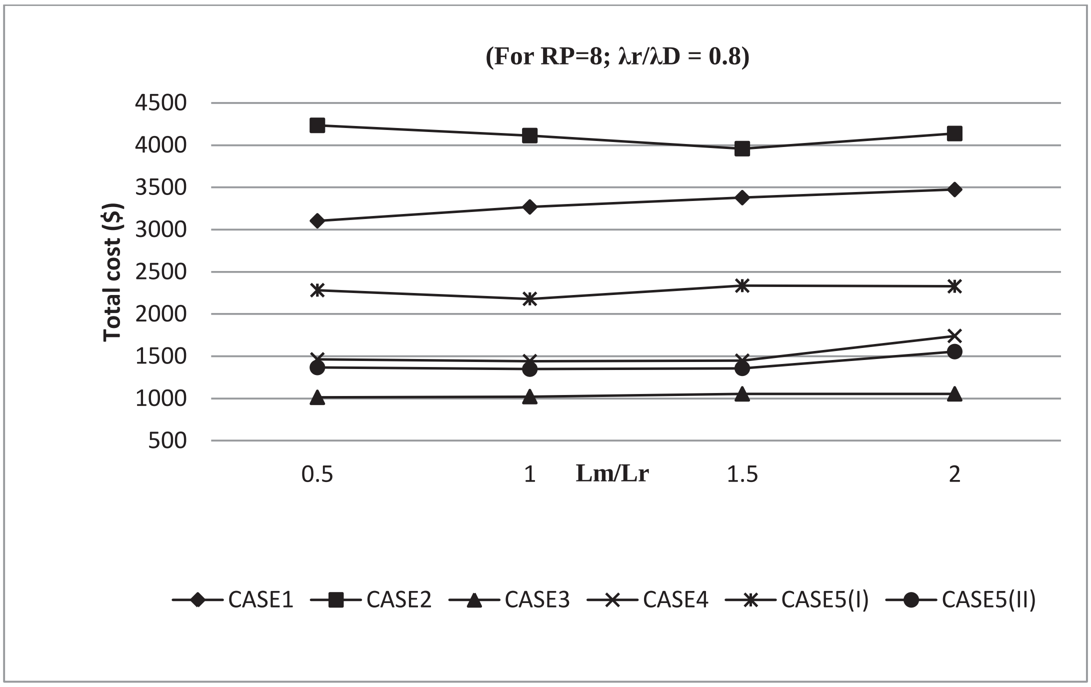
Figure 4: Total inventory cost for five cases with ((a) RP=4, (b) RP=6 and (c) RP=8; $\lambda_r/\lambda_D = 0.5$)


(For RP=4; λr/λD = 0.8)
Total cost ($)
4500
4000
3500
3000
2500
2000
1500
1000
0.5
1
1.5
2
Lm/Lr
CASE1
CASE2
CASE3
CASE4
CASE5(I)
CASE5(II)

5(a)


(For RP=6; λr/λD = 0.8)
Total cost ($)
4500
4000
3500
3000
2500
2000
1500
1000
500
0.5
1
1.5
2
Lm/Lr
CASE1
CASE2
CASE3
CASE4
CASE5(I)
CASE5(II)

5(b)



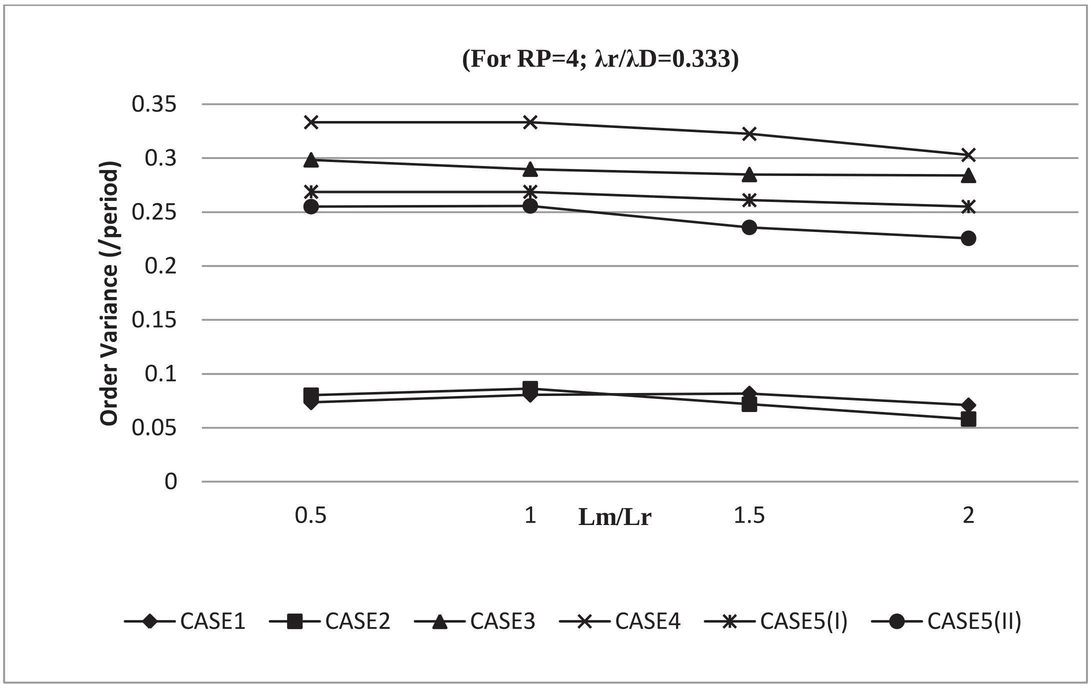
5(c)

Figure 5: Total inventory cost for five cases with ((a) RP=4, (b) RP=6 and (c) RP=8; $\lambda_r/\lambda_D = 0.8$)

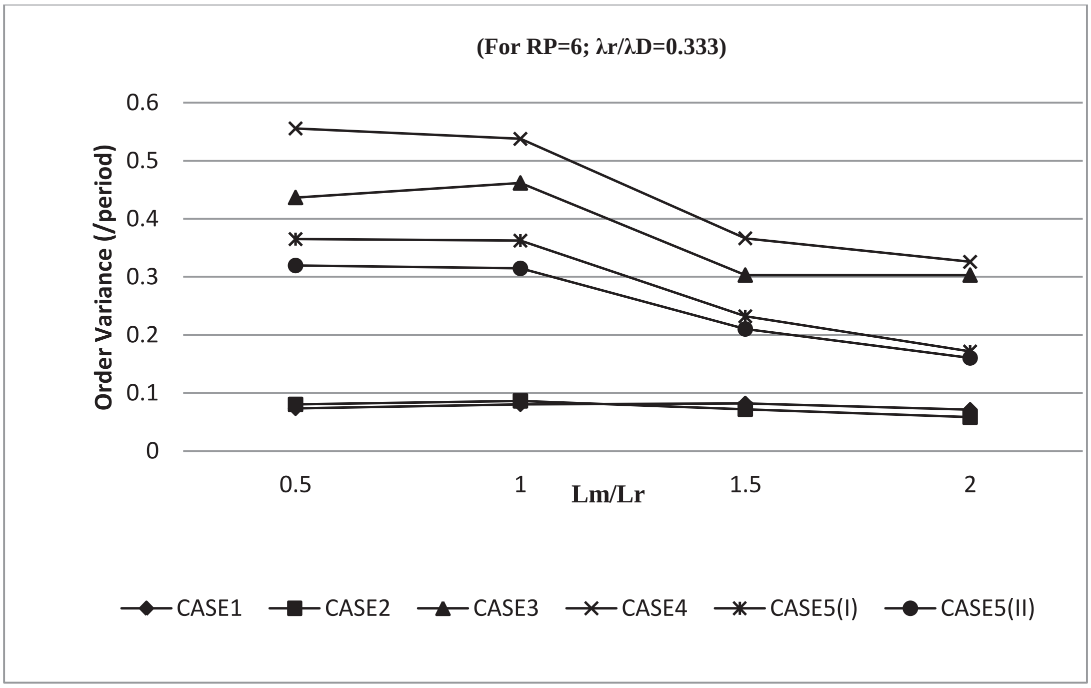
Figure 6 – 8 depict the order variance under similar parameters of a continuous and periodic review system as specified for total inventory cost performance. The variances are determined with the intention of studying the impact of review policies on the bullwhip effect. The order variance determined for production considers the effect of both manufacturing and remanufacturing. The figures show that for a given ratio of λ_r/λ_D, the increasing values of manufacturing lead time (i.e. for increasing values of L_m/L_r ratio) have no effect on variance for the continuous review system. The result is consistent with the findings of Corum et al. (2014) for the continuous review system.

However, the variance decreases with the increasing values of manufacturing lead time in the periodic review system. The result may be the outcome of synchronization of the review period and manufacturing lead time. Furthermore, the variance increases with increasing values of the review period. This may be explained by the fact that in the periodic review system, the lot sizes are relatively higher and less frequent manufacturing orders are likely to occur. As seen in Figure 8, the variance significantly decreases for periodic review policies with the lower value of demand rate (i.e., the increasing value of λ_r/λ_D ratio). This shows the appreciable role of remanufacturing in mitigating the bullwhip effect by strategically adopting periodic review policies.

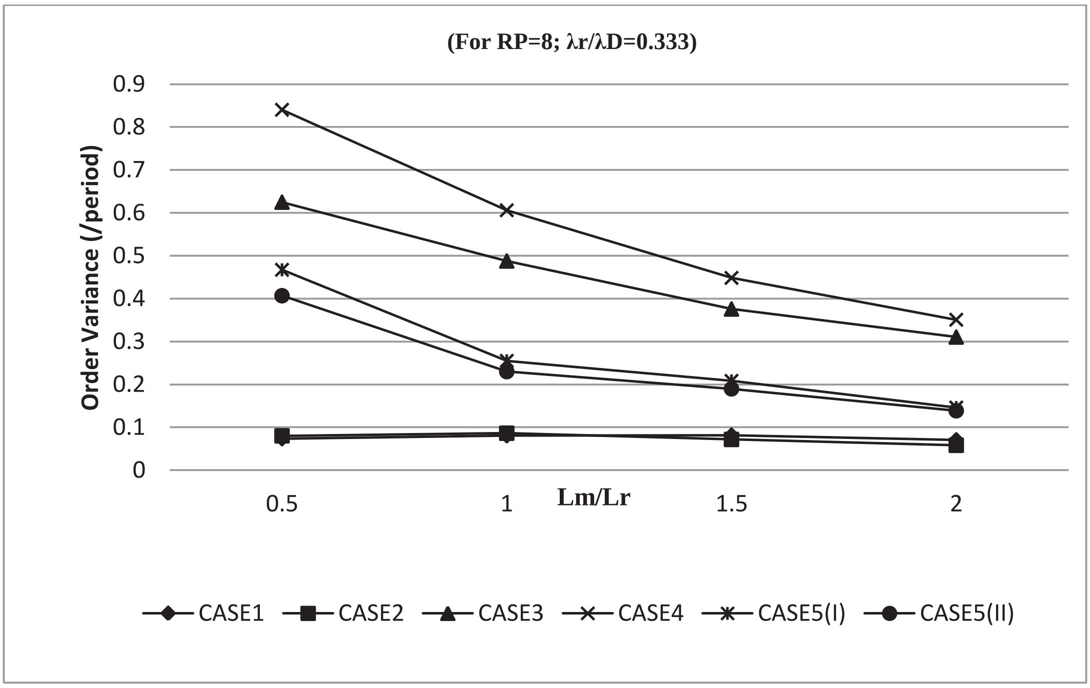
We now discuss the results comparing the cases pertaining to periodic review policies (i.e., for Case3 through Case 5 (I&II)) from an order variance perspective. In Figure 6, it is seen that Case5 (II) outperforms other periodic review cases. From the result, it is apparent that given the high demand rate (i.e., the low value of $\lambda_r/\ \lambda_D$ ratio), it is beneficial to prioritize the remanufacturing. This may be explained by the fact that small and frequent remanufacturing lot sizes would tend to keep the variance low. Furthermore, in Figure 8, given the low value of demand rate (i.e., the high value of $\lambda_r/\ \lambda_D$ ratio) it is seen that Case4 outperforms the other periodic review cases. In Figure 8(c), we find that Case4 outperforms even continuous review policies for higher values of lead time. The result again illustrates the appreciable contribution of remanufacturing in which all the return parts are remanufactured.


(For RP=4; λr/λD=0.333)
Order Variance (/period)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.5
1
Lm/Lr
1.5
2
CASE1
CASE2
CASE3
CASE4
CASE5(I)
CASE5(II)

6(a)

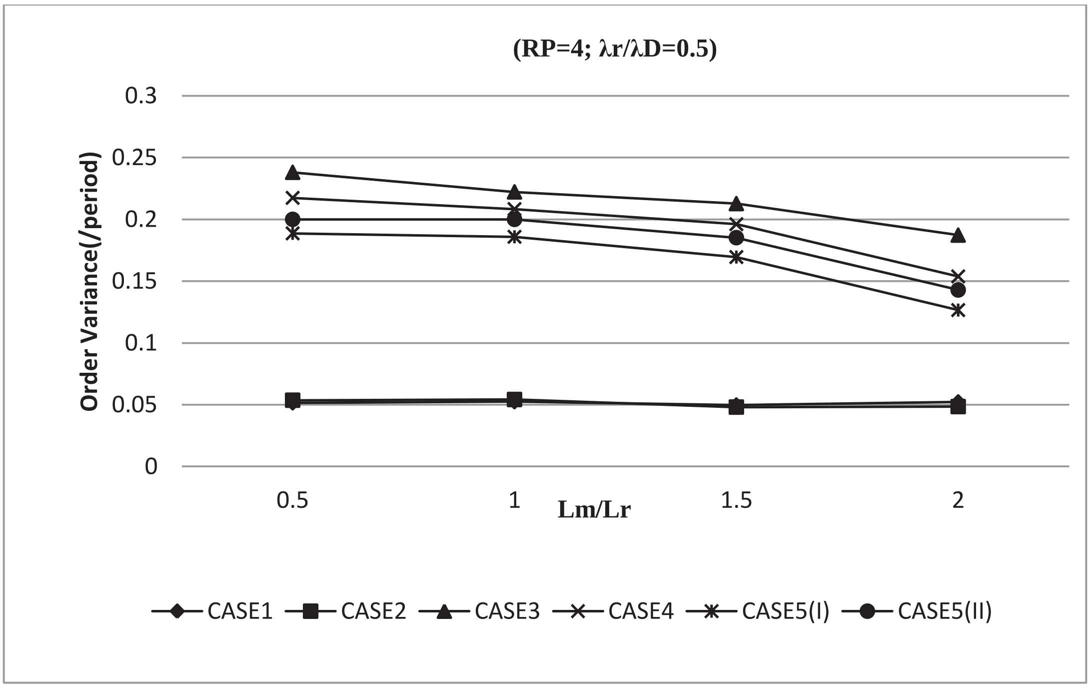

(For RP=6; λr/λD=0.333)
Order Variance (/period)
0.6
0.5
0.4
0.3
0.2
0.1
0
0.5
1
Lm/Lr
1.5
2
CASE1
CASE2
CASE3
CASE4
CASE5(I)
CASE5(II)

6(b)

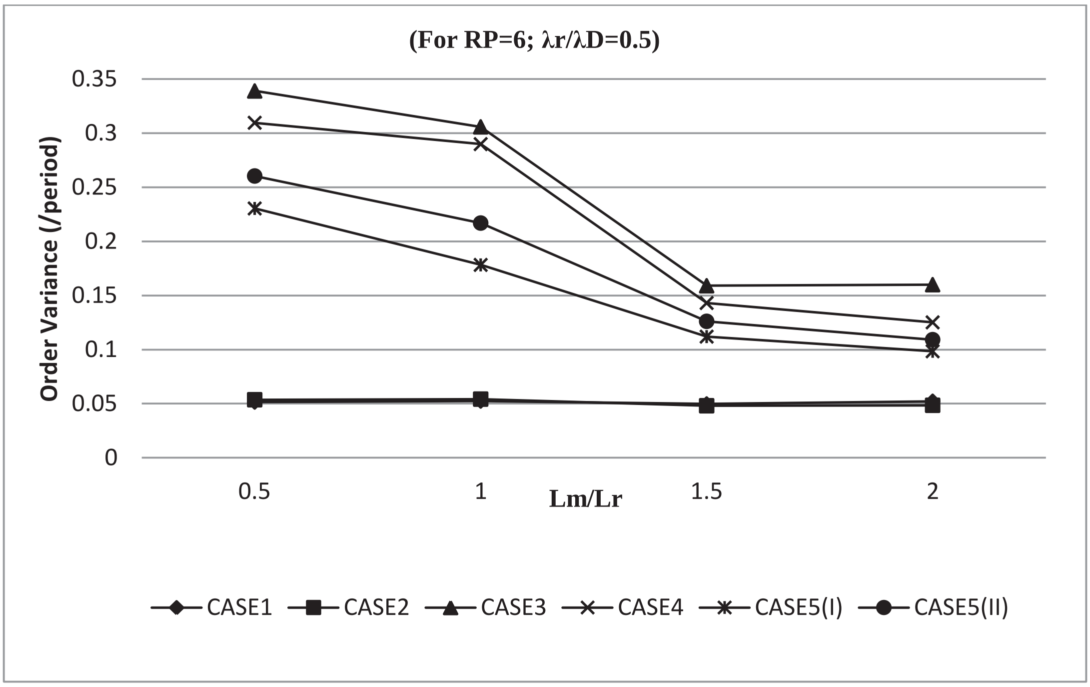


6(c)

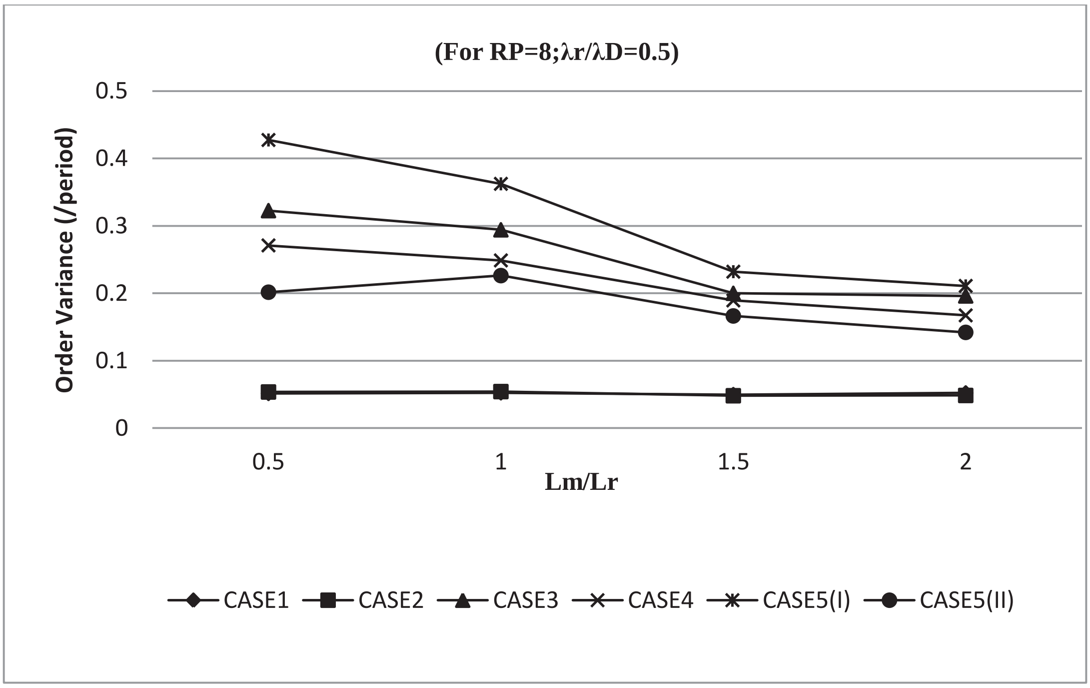
Figure 6: Order variance for the five cases with ((a) RP=4, (b) RP=6 and (c) RP=8; λ_r / λ_D = 0.333)



7(a)

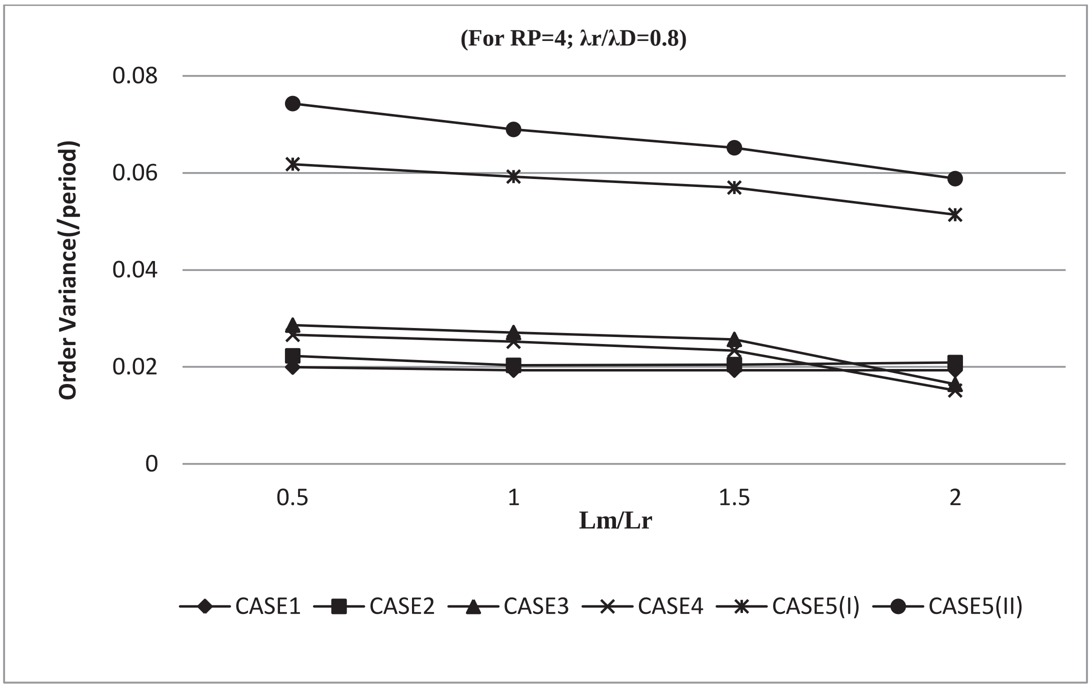


7(b)



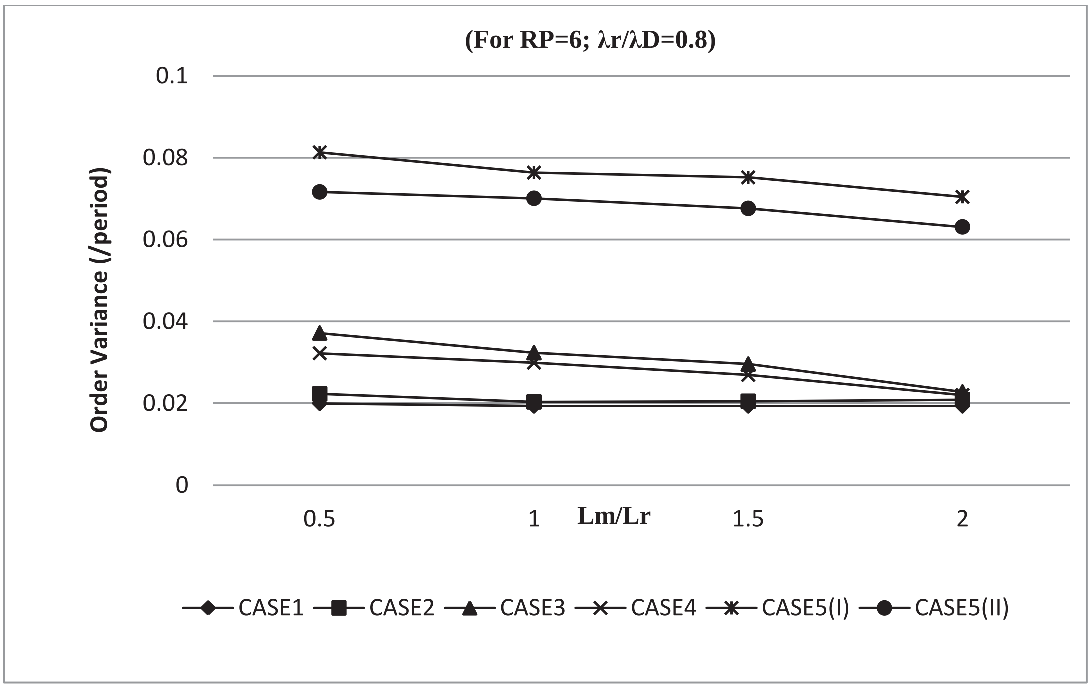
7(c)

Figure 7: Order variance for the five cases with ((a) RP=4, (b) RP=6 and (c) RP=8; $\lambda_r / \lambda_D = 0.5$)



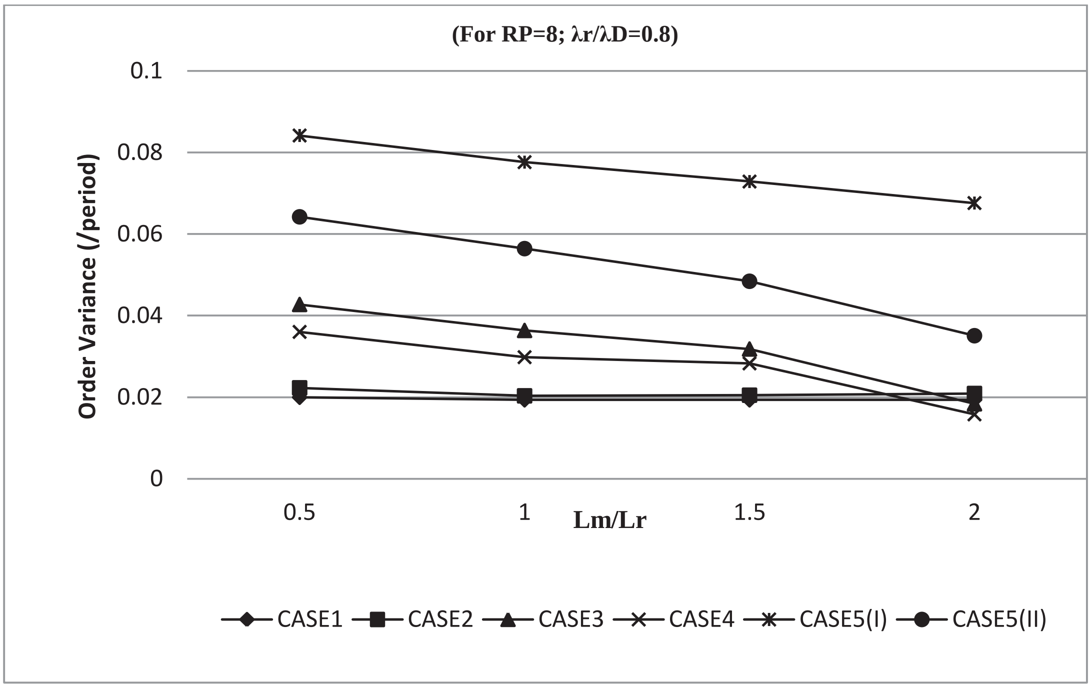
(For RP=4; λr/λD=0.8)
0.08
0.06
0.04
0.02
0
Order Variance(/period)
0.5
1
1.5
2
Lm/Lr
CASE1
CASE2
CASE3
CASE4
CASE5(I)
CASE5(II)

8(a)



(For RP=6; λr/λD=0.8)
0.1
0.08
0.06
0.04
0.02
0
Order Variance (/period)
0.5
1
Lm/Lr
1.5
2
CASE1
CASE2
CASE3
CASE4
CASE5(I)
CASE5(II)

8(b)



8(c)

Figure 8: Order variance for the five cases with ((a) RP=4, (b) RP=6 and (c) RP=8; $\lambda_r/\lambda_D = 0.8$)

6. Conclusions

Product recovery has been a source of motivation for the contemporary business organizations. Remanufacturing has emerged as an important alternative means of material recovery. The manufacturing and remanufacturing processes are jointly used in hybrid systems to satisfy the demand. In literature, researchers have comprehensively used inventory and production planning models to support the hybrid systems in the material recovery process. However, in these researches, the inventory management is realized through either a continuous or periodic review system. We could scarcely find any research that addresses the issue of the impact of both continuous and periodic review systems on a closed-loop hybrid supply chain operations. Considering the comprehensive review by Akçali and Çetinkaya (2011) as the basis, in this paper, we fill the current research gap of I&PP models by comparing the continuous and periodic review policy systems for total inventory cost and production order variance performances. The impact of different parameters, such as stochastic demand and return rates, stochastic manufacturing and remanufacturing lead times, is studied through developing simulation models for five different cases from the literature concerning continuous and periodic review systems. From the serviceable and recoverable inventory cost viewpoint, there is a trade-off between periodic review policy and continuous review policy which generates a threshold value of total inventory cost with the change in values of return rate to demand rate ratio (λ_r/ λ_D). Thus, this analysis provides leverage to the decision maker for strategically adopting the operational units so as to enhance the total inventory cost performance.

Furthermore, from the order variance point of view, continuous review policies outperform all cases of periodic review policies considered. However, for low demand rate, such as for slow moving products, the slow depletion of manufactured inventory is offset by the remanufactured items that lead to frequent depletion of smaller lot size, leading to low order variance. Thus, this analysis provides leverage to the decision maker for strategically adopting the appropriate periodic review policy for low demand rate products. For example, as seen in Figure 8, case3 and case4 of periodic review policy outperforms even continuous review policy for the higher values of L_m/L_r ratio. Therefore, appropriate adoption of periodic review policy helps in mitigating the bullwhip effect.

Thus, the present paper bridges the gap in terms of trade-off analysis of continuous and periodic review policies concerning closed-loop hybrid systems. However, experimental design setup deserves further attention in terms of parameterization and the effect of capacity restrictions and thereby disposal options. The effect of lost sales can also be analyzed by considering the back orders in the cost function. These variations provide scope for future work.

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Figure(s)

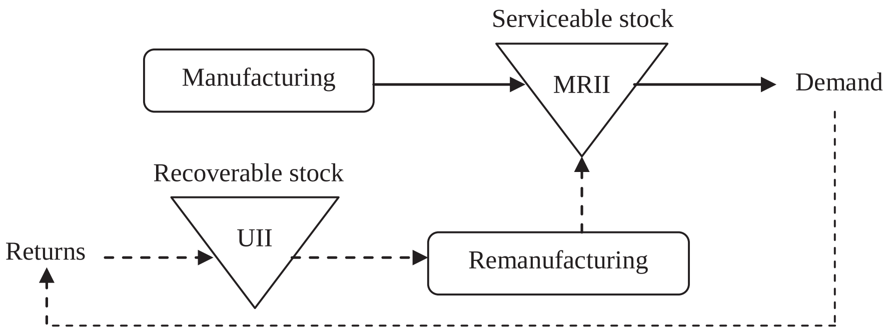


Figure 1: Hybrid inventory system with manufacturing and remanufacturing systems (Akçali and Çetinkaya 2011)

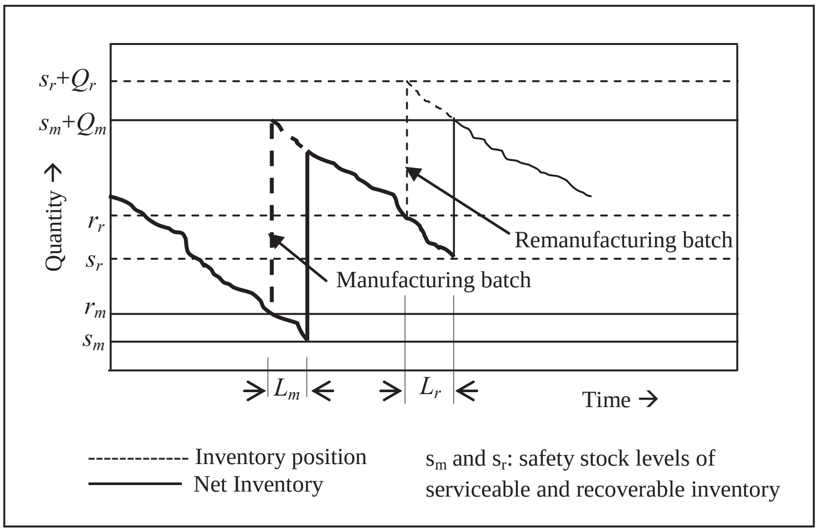


Figure 2(a): Hybrid system under continuous review policy

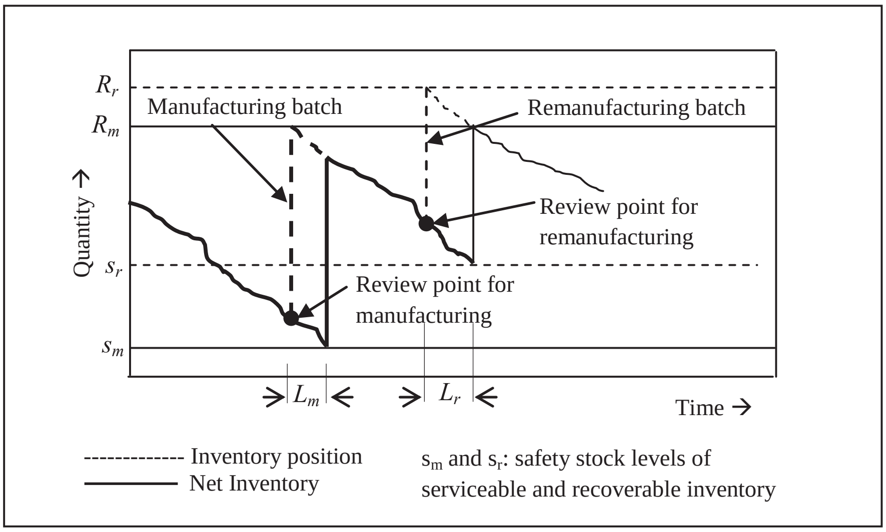
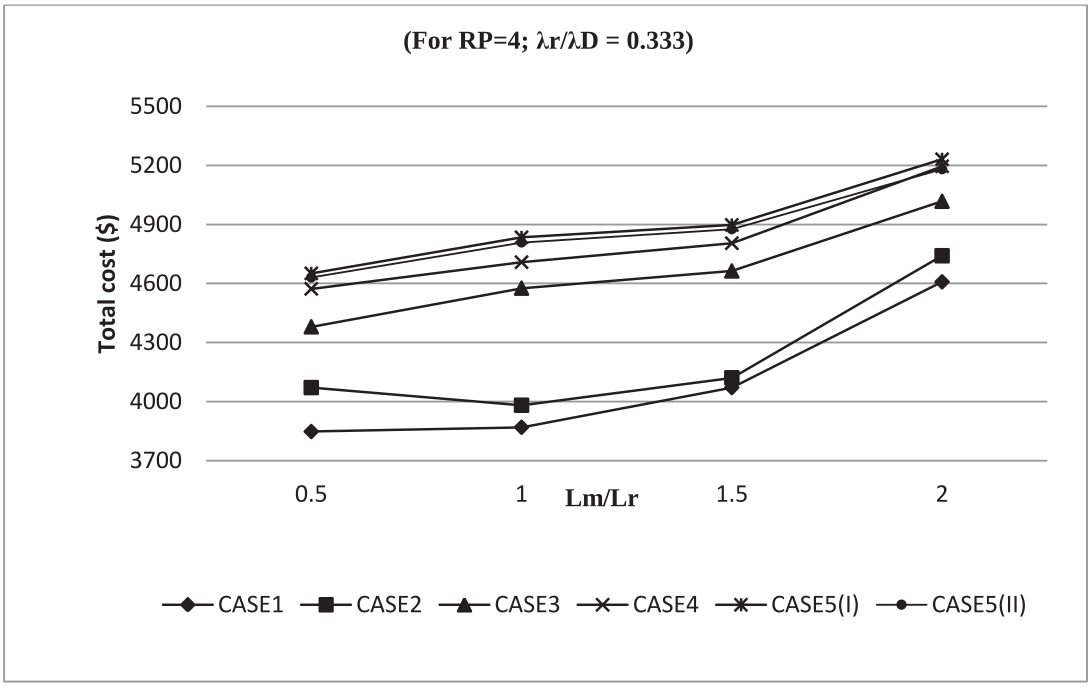
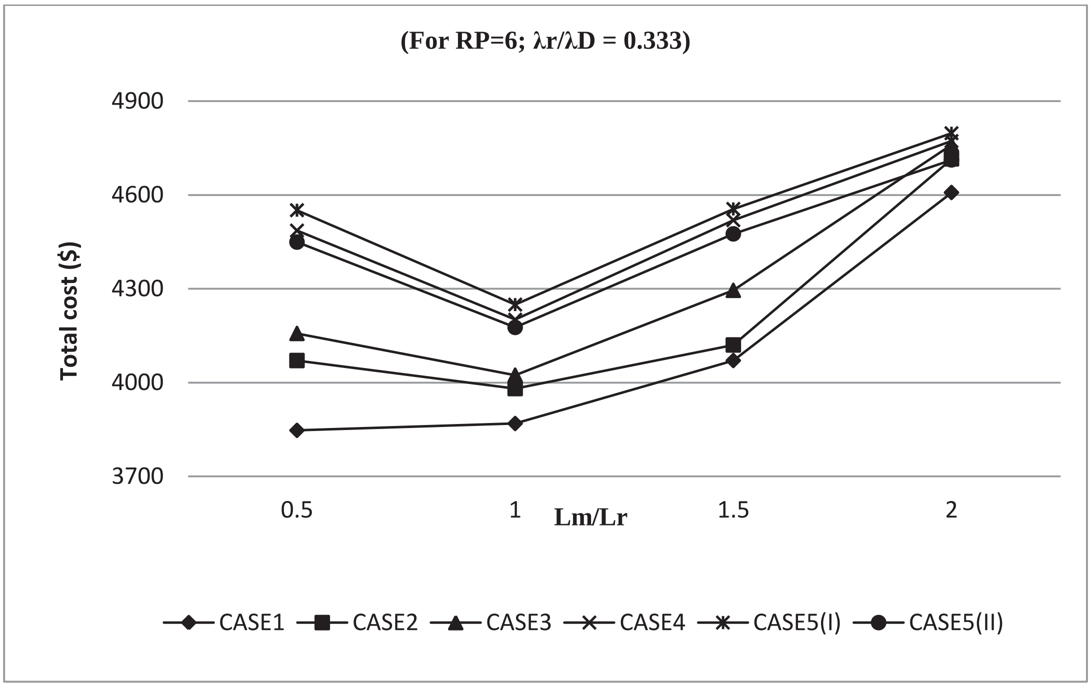


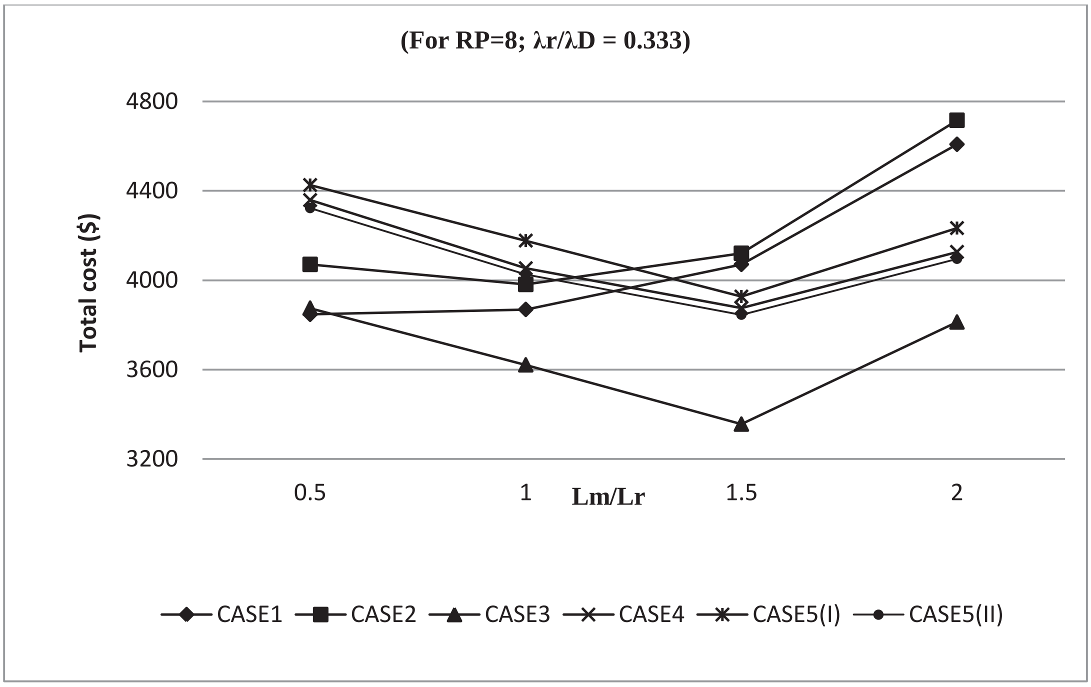
Figure 2(b): Hybrid system under periodic review policy



3(a)

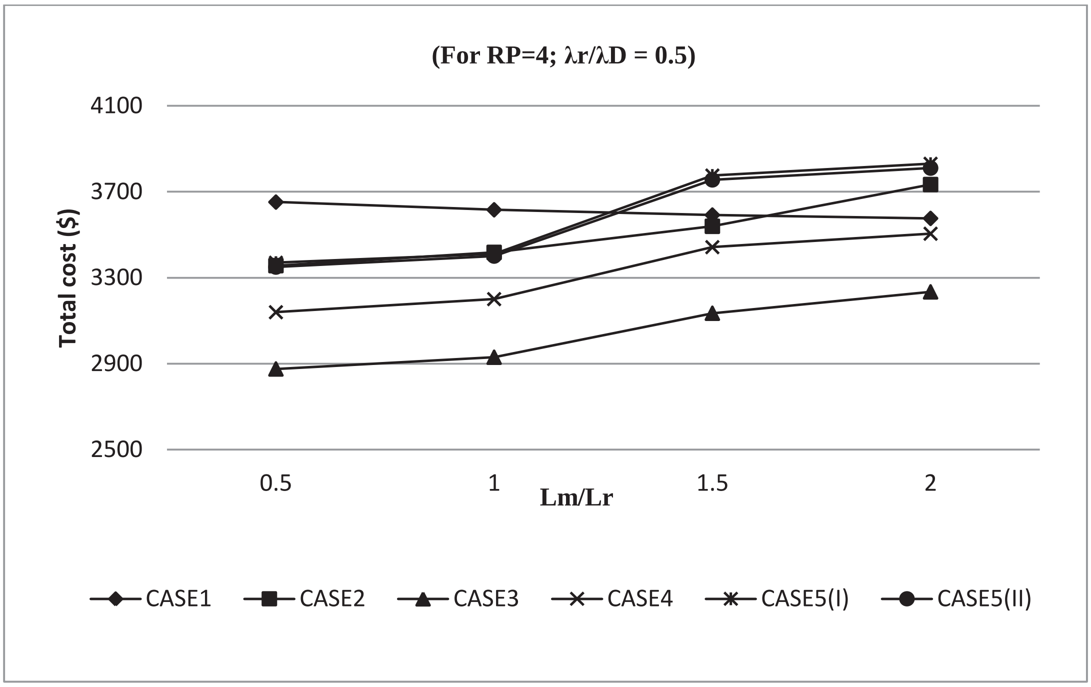


3(b)

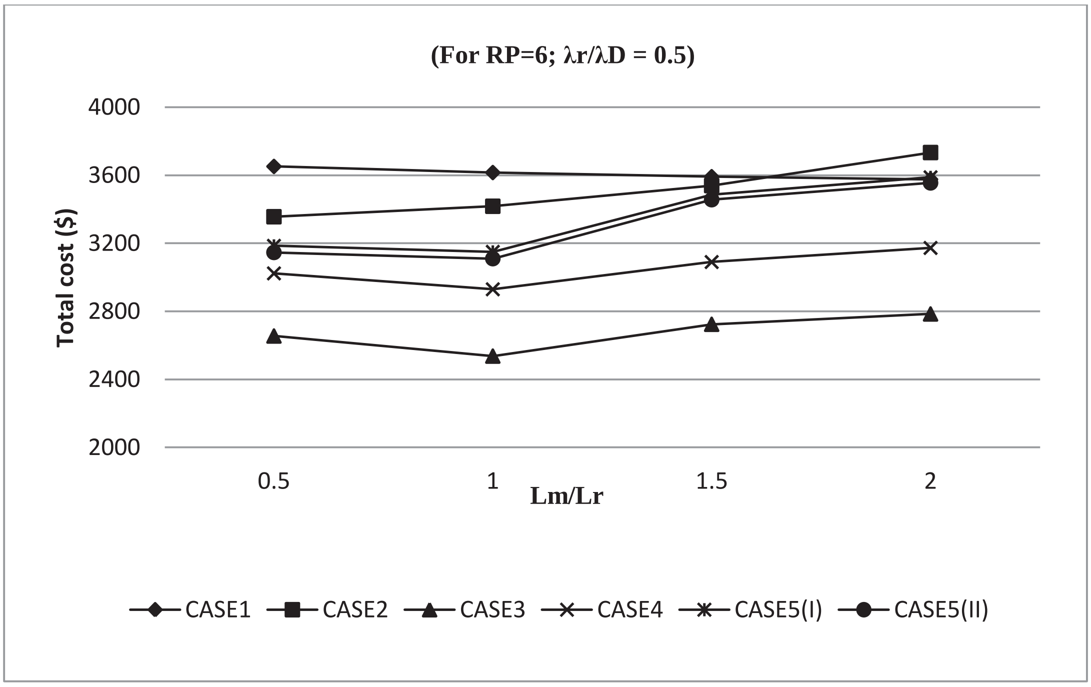


3(c)

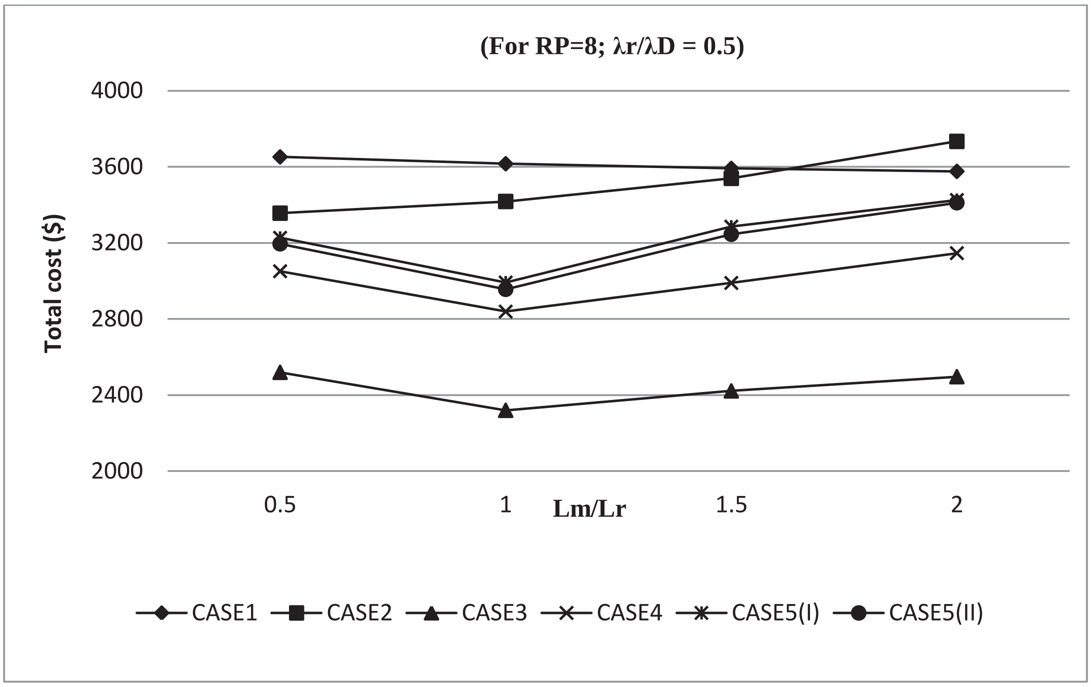
Figure 3: Total inventory cost for five cases with ((a) RP=4, (b) RP=6 and (c) RP=8; λ_r / λ_D = 0.333)


(For RP=4; λr/λD = 0.5)
4100
3700
3300
2900
2500
Total cost ($)
0.5
1
1.5
2
Lm/Lr
CASE1
CASE2
CASE3
CASE4
CASE5(I)
CASE5(II)

4(a)

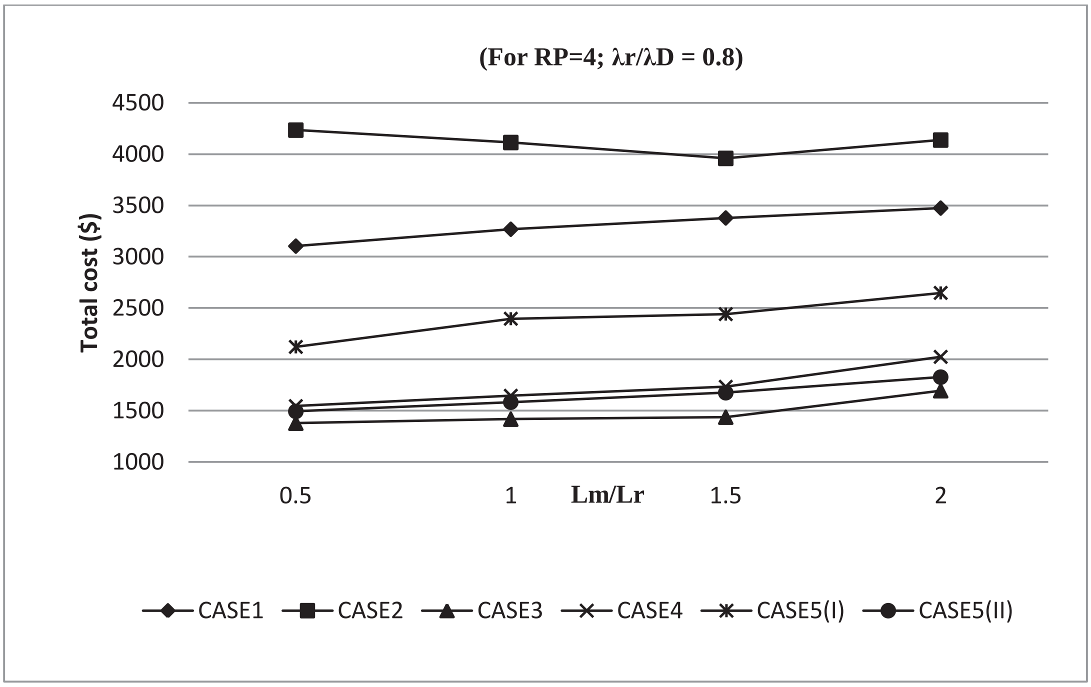

(For RP=6; λr/λD = 0.5)
4000
3600
3200
2800
2400
2000
Total cost ($)
0.5
1
1.5
2
Lm/Lr
CASE1
CASE2
CASE3
CASE4
CASE5(I)
CASE5(II)

4(b)

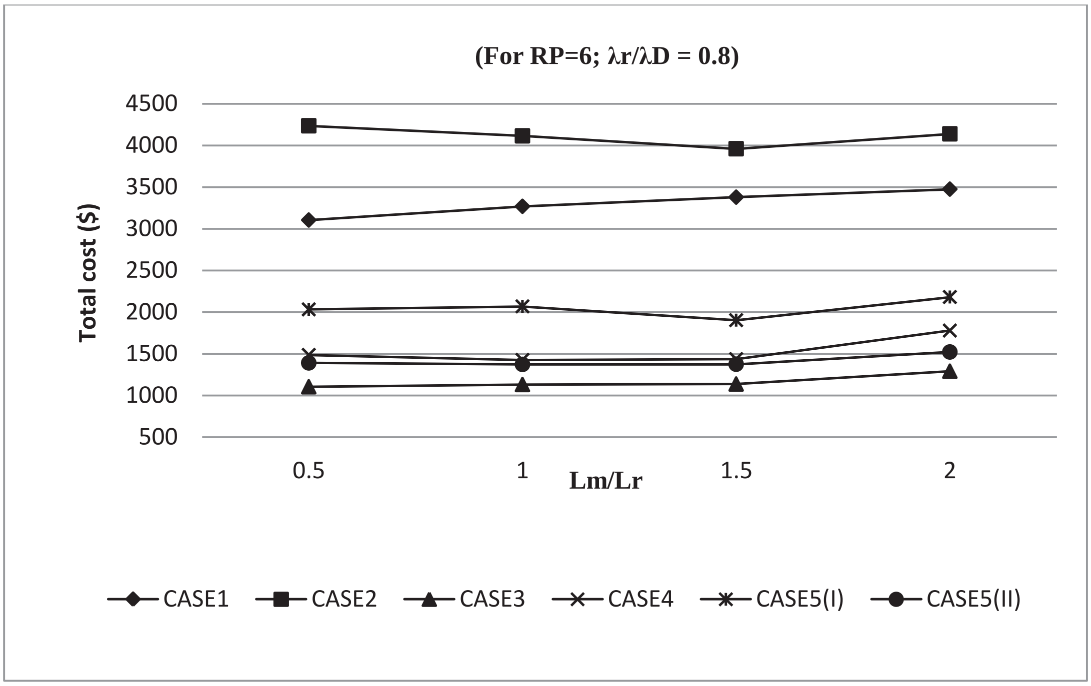


4(c)

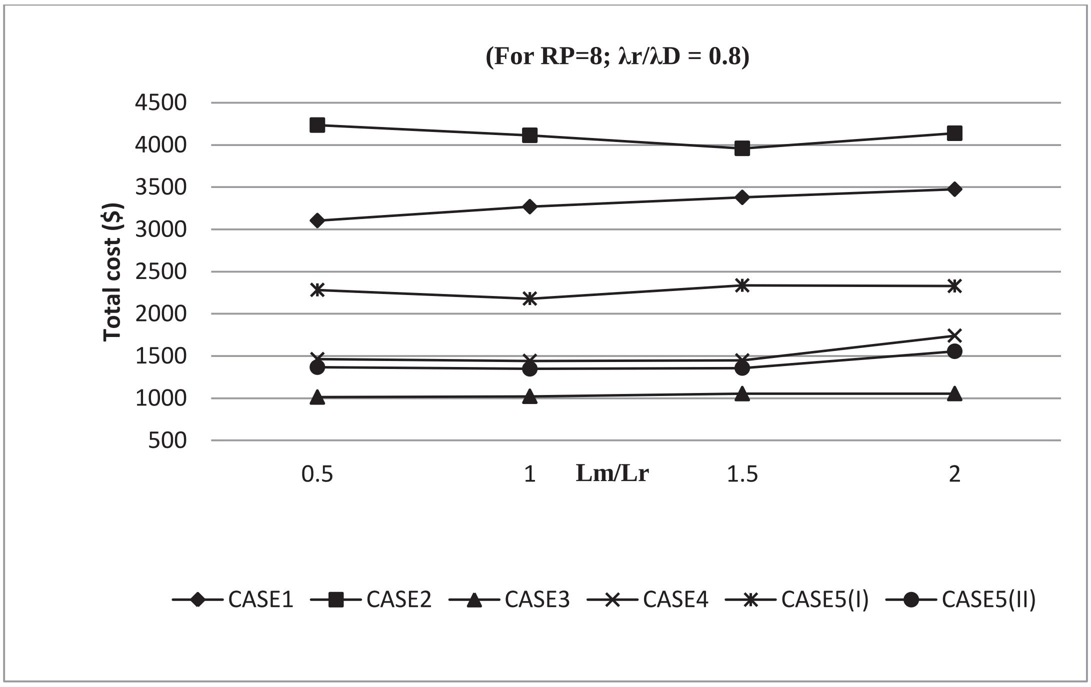
Figure 4: Total inventory cost for five cases with ((a) RP=4, (b) RP=6 and (c) RP=8; $\lambda_r/\lambda_D = 0.5$)



5(a)

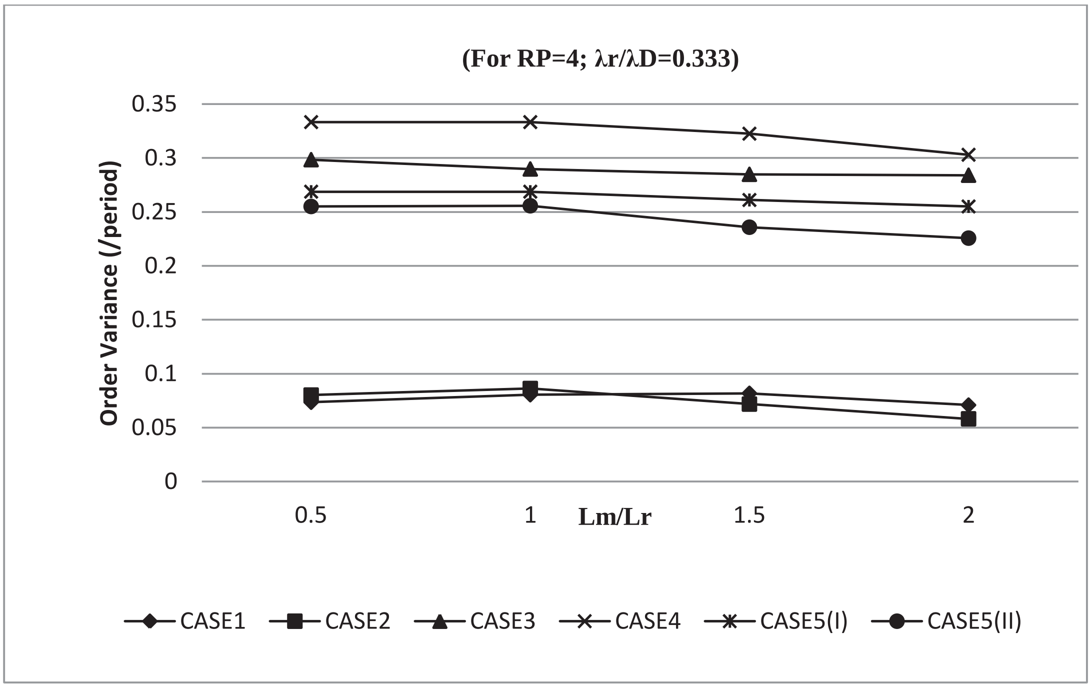


5(b)

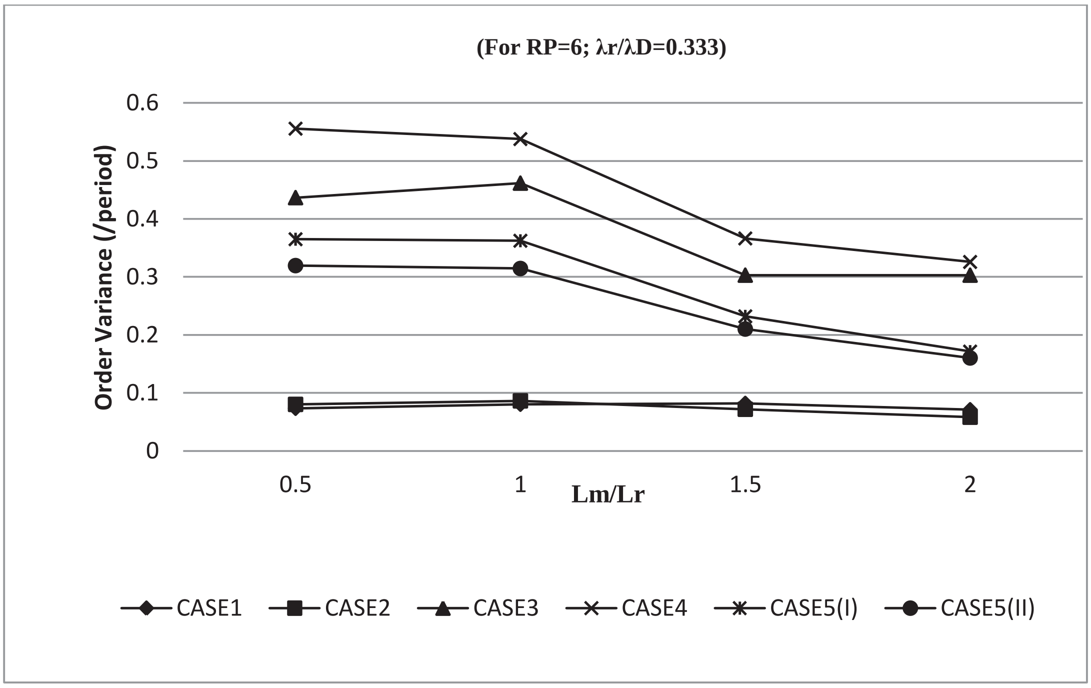


5(c)

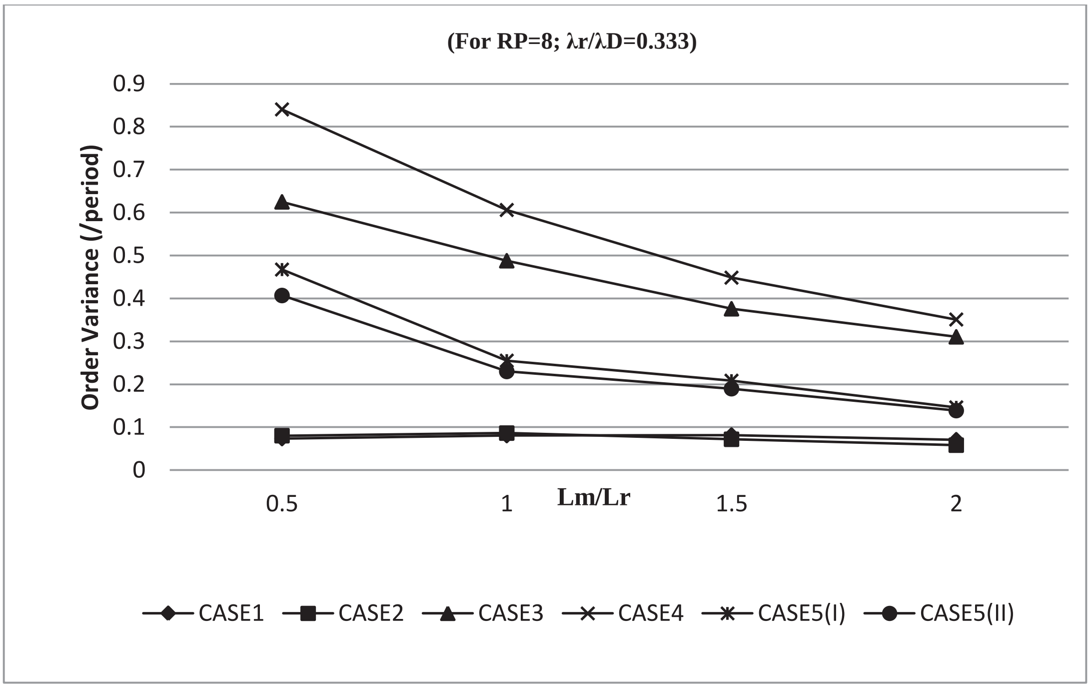
Figure 5: Total inventory cost for five cases with ((a) RP=4, (b) RP=6 and (c) RP=8; $\lambda_r / \lambda_D = 0.8$)


(For RP=4; λr/λD=0.333)
Order Variance (/period)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.5
1
1.5
2
Lm/Lr
CASE1
CASE2
CASE3
CASE4
CASE5(I)
CASE5(II)

6(a)

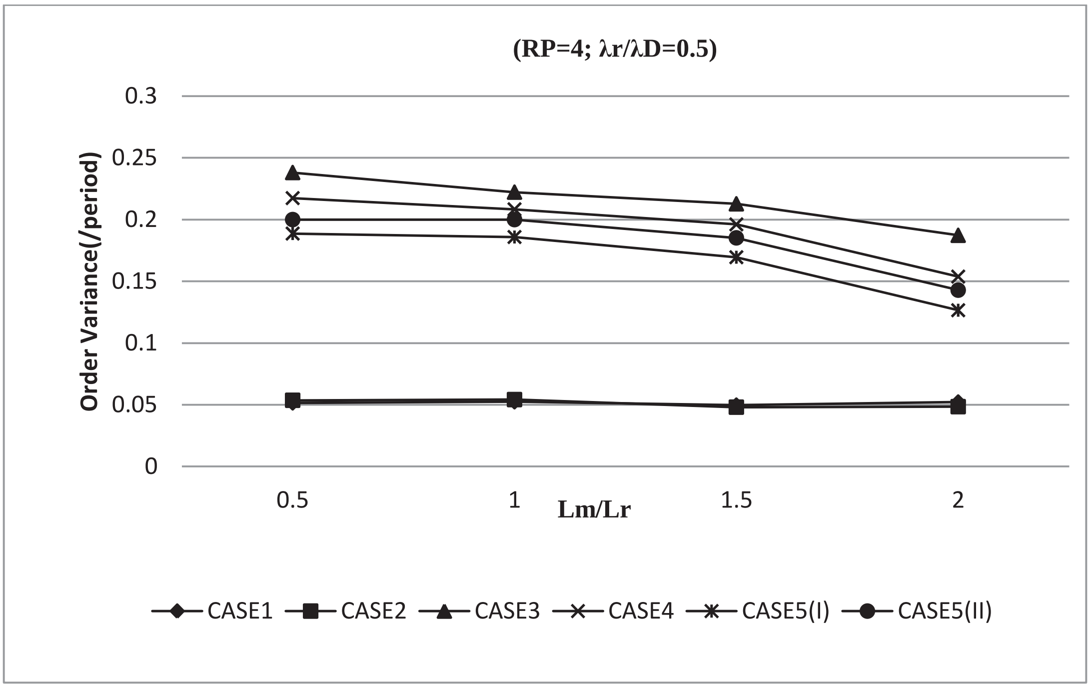

(For RP=6; λr/λD=0.333)
Order Variance (/period)
0.6
0.5
0.4
0.3
0.2
0.1
0
0.5
1
1.5
2
Lm/Lr
CASE1
CASE2
CASE3
CASE4
CASE5(I)
CASE5(II)

6(b)

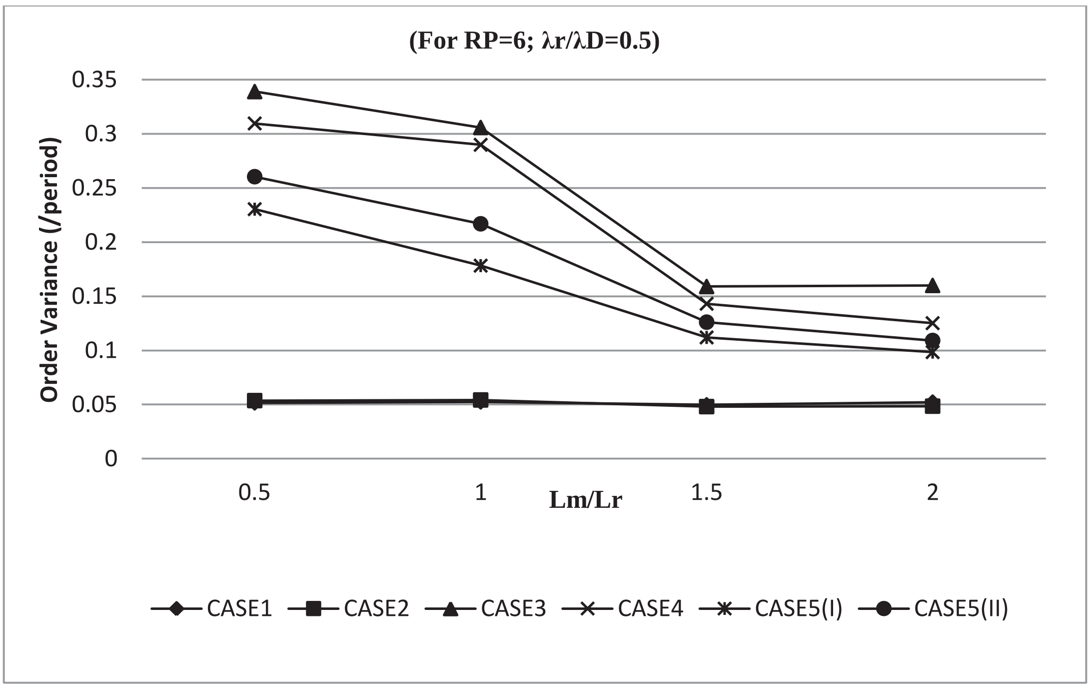


6(c)

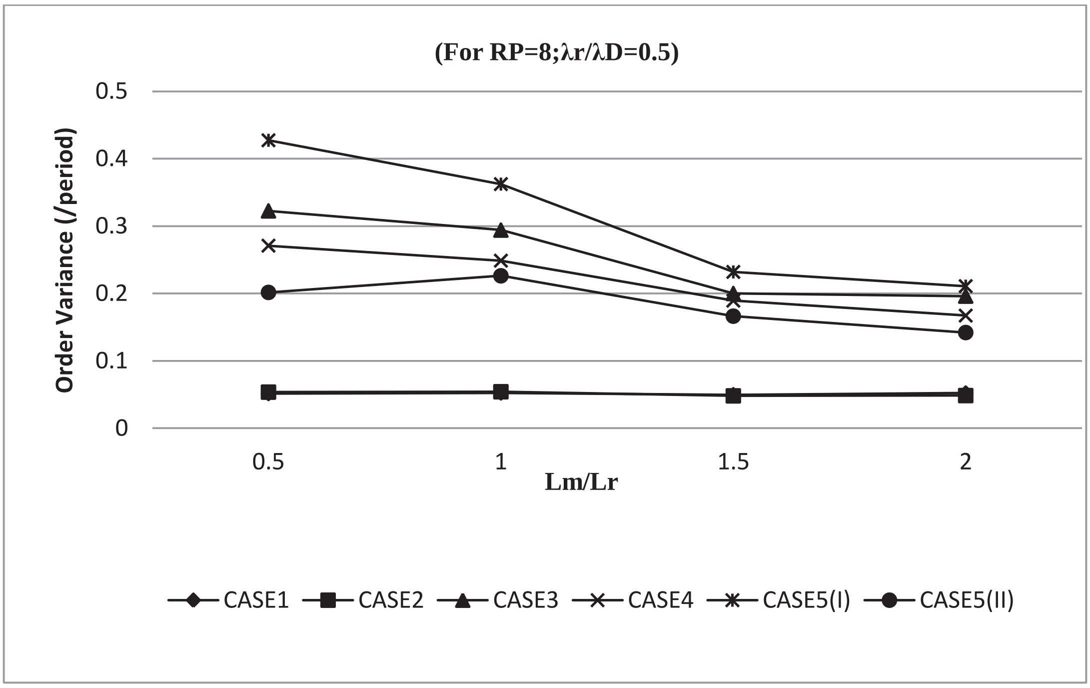
Figure 6: Order variance for the five cases with ((a) RP=4, (b) RP=6 and (c) RP=8; λ_r / λ_D = 0.333)


(RP=4; λr/λD=0.5)
Order Variance(/period)
0.3
0.25
0.2
0.15
0.1
0.05
0
0.5
1
1.5
2
Lm/Lr
CASE1
CASE2
CASE3
CASE4
CASE5(I)
CASE5(II)

7(a)

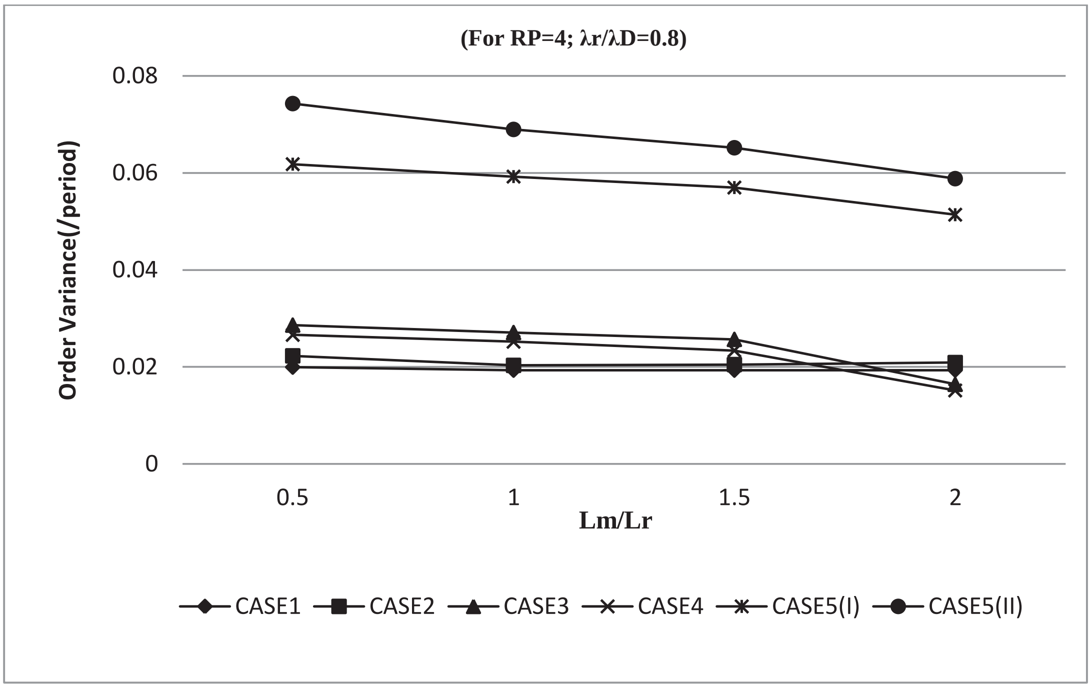

(For RP=6; λr/λD=0.5)
Order Variance (/period)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.5
1
1.5
2
Lm/Lr
CASE1
CASE2
CASE3
CASE4
CASE5(I)
CASE5(II)

7(b)

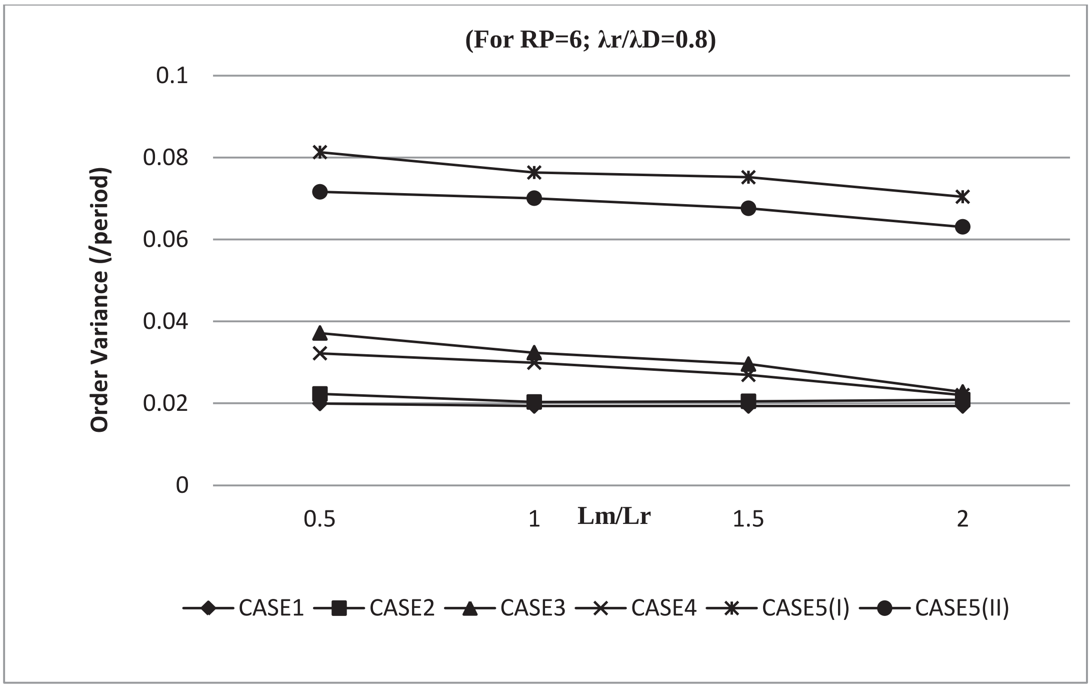


7(c)

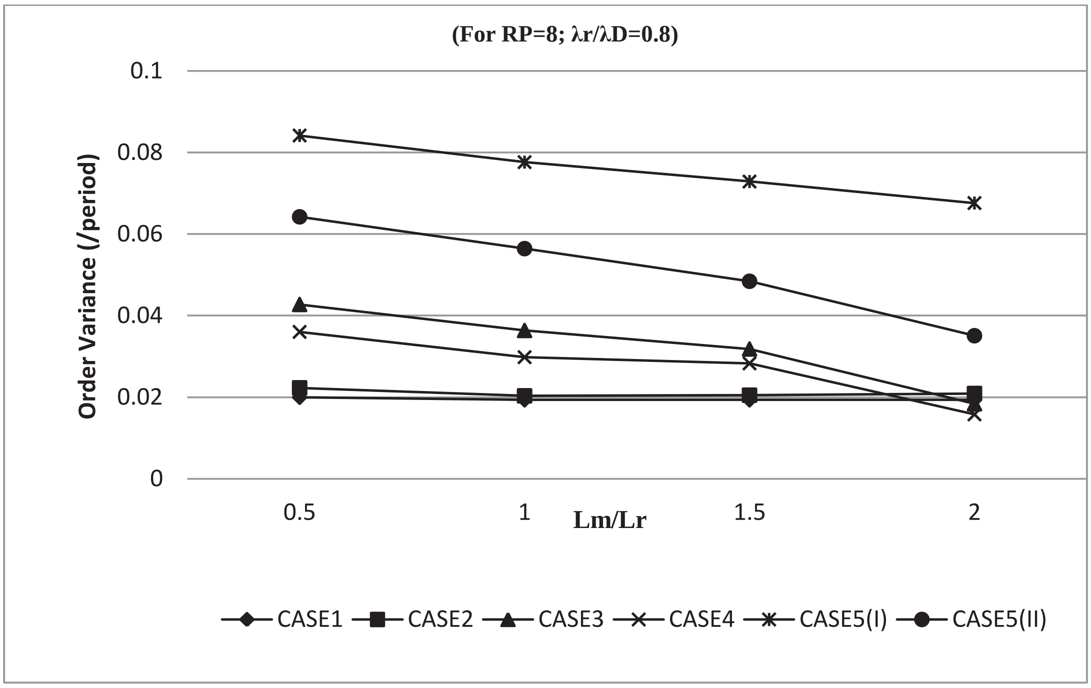
Figure 7: Order variance for the five cases with ((a) RP=4, (b) RP=6 and (c) RP=8; $\lambda_r / \lambda_D = 0.5$)


(For RP=4; λr/λD=0.8)
0.08
0.06
0.04
0.02
0
Order Variance(/period)
0.5
1
1.5
2
Lm/Lr
CASE1
CASE2
CASE3
CASE4
CASE5(I)
CASE5(II)

8(a)


(For RP=6; λr/λD=0.8)
0.1
0.08
0.06
0.04
0.02
0
Order Variance (/period)
0.5
1
Lm/Lr
1.5
2
CASE1
CASE2
CASE3
CASE4
CASE5(I)
CASE5(II)

8(b)



8(c)

Figure 8: Order variance for the five cases with ((a) RP=4, (b) RP=6 and (c) RP=8; $\lambda_r / \lambda_D = 0.8$)

Table(s)

Table 1: Overview of experimental factors and levels

Fixed Factors	
Demand rate (units/period)(λ_D)	EXPO(12); EXPO(8); EXPO(5)
Return rate (units/period)(λ_r)	EXPO(4)
Remanufacturing lead time N(L_r, σ_r^2)	(4,1)
Manufacturing lead time N(L_m, σ_m^2)	(2,1); (4, 1); (6, 1); (8, 1)
Remanufacturing set-up cost K_r ($/batch)	$10
Manufacturing set-up cost K_m ($/batch)	$50
Inventory holding rate (i) (%/1000 periods)	5%
Holding cost of serviceable inventory h_s ($/1000 periods/unit)	200*i
Holding cost of recoverable inventory h_r ($/1000 periods/unit)	20*i
Experimental Factors	
Review Period (periods)	4; 6; 8
Inventory policy	Continuous (r, Q); Periodic (order up-to level)
I&PP control policies	Case1 through Case 5