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by

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Abstract

Vendor managed inventory is a well established supply chain coordination practice wherein the supplier is responsible for managing the inventory at the retail points. In particular, the supplier takes care of, *when to order* and *how much to order* on behalf of the retailers. This paper considers a single vendor – multiple retailer setting where vendor takes inventory replenishment decisions for retailers such that the replenishment quantities are within an upper bound that is mutually agreed upon in the contractual agreement. Although various replenishment models under such a setting have been developed in the literature, this paper develops a generalized joint replenishment model by highlighting the role of *cycle ratio(setup cost/holding cost * demand)*. We compute the optimal replenishment frequency, quantity and total cost. We also show that our model leads to the minimum cost in general as compared to the existing models that give minimum cost only under certain specific conditions.

Keywords

(D) Supply chain management, Multi-Item Joint Replenishment, Vendor Managed Inventory, Inventory Management

1. Introduction and literature review

Supply chain(SC) as a concept fails to deliver its purpose unless various entities of it realizes the importance of coordination mechanisms. Supply chain coordination can be thought of as a strategic response to the inter-firm dependencies in a SC (Xu & Beamon, 2006). It can be defined as “ an instrument for managing dependencies between various entities” (Malone & Crowston, 1994). The consequences of having a coordination-less supply chain are realized in the form of excessive inventory, low capacity utilization, low quality, low customer satisfaction (Ramdas & Spekman, 2000). On the other hand, having a well coordinated supply chain helps in reducing excessive inventory, tackling demand uncertainty, flexibly (Horvath, 2001; Lee, Padmanabhan & Whang, 1997). Vendor managed inventory is such a coordination mechanism, popularized by Wal-Mart and P&G in 1980's (Waller, Johnson, & Davis, 1999). Since then, it has proved to be one of the successful supply chain integration and coordination mechanism (Danese, 2006; Pohlen & Goldspy, 2003).

VMI over the time has evolved in different forms. In one of the forms the ownership of the items remain with the supplier until those are sold. This is referred to as VMI on consignment (Valentini & Zavanella, 2003; Wang, Jiang & Shen, 2004). In some other cases, supplier receives the money as soon as items are transferred to the customers(retailers). This is known as VMI (Fry, Kapuscinski & Olsen, 2001; Lee & Chu, 2005). Irrespective of the kind of form adopted by various companies, VMI in general has proved beneficial in terms of reduced inventory cost, improved customer service level, greater transparency and fill rate (Angulo, Nachtmann & Waller, 2004; Cetinkaya & Lee, 2000; Waller et al., 1999). Losses due to demand fluctuations also get reduced in the VMI environment as supplier is directly monitoring the inventory at the retailer's space thus giving it more comfort for replenishing it (Yao, Evers & Dresner, 2007). Moreover, the availability of the information helps to reduce the Bullwhip effect (Reiner & Trcka, 2004). From the retailer's perspective the benefits come from the reduced administrative cost as they are no more responsible for placing the order themselves (Aichlmayr, 2000).

With any coordination mechanism for a SC, many issues such as contract design, information sharing, competition dynamics etc. emerges simultaneously. Vendor managed inventory being a coordination mechanism, also incorporates such issues. Mathematical modelling of such issues to understand them deeply has been conducted in the VMI literature quite well over the course of time. The modelling literature of VMI, includes studies like evaluation of the time-benefit the supplier has under VMI (Kaipia, Holmström & Tanskanen, 2002), shipment coordination mechanisms (Cheung & Lee, 2002), inventory cost sharing under VMI (Nagrajan & Rajagopalan, 2008), shipment consolidation by the supplier (Cetinkaya, Tekin & Lee, 2008) etc.

Apart from the issues stated above, another area that has received researchers attention is of devising optimal replenishment policies under VMI. Some of the papers in the VMI literature consider replenishment policies for single supplier – single retailer setting. Yao et al. (2007) studies the same, bringing out the incremental benefits with VMI as coordination mechanism.

Other studies under such a setting are taken up by Van der Vlist, Kuik and Verheijen (2007), Wang, Wee and Tsao (2010), Huang and Ye (2010) etc. Single supplier – multiple retailer setting have also received its share of attention in the VMI literature. Viswanathan and Piplani (2001) proposes a replenishment policy under which the supplier sets up at fixed intervals/epochs and retailers get replenished at those intervals/epochs only. Zhanga, Liang, Yu and Yu (2007) develops a model by considering supplier's production cycle as constant and retailers having different replenishment cycles. Zavanella and Zanoni (2009) studies such a VMI setting under consignment.

Some studies in the literature situate themselves in a single supplier – multiple retailer setting with additional contractual constraints such as storage limits. Darwish & Odah (2010) devises a replenishment policy wherein the retailers have equal replenishment intervals(ERI). Hariga, Gumus, Daghfous and Goyal (2013) and Verma, Chakraborty and Chatterjee (2013) generalizes their model by relaxing the assumption of ERI by allowing retailers to have unequal replenishment intervals(URI). The inherent assumption in the above papers is that the retailers are homogeneous with respect to their cycle ratios. This paper too, situates itself in a single supplier – multiple retailer VMI environment with contractual storage agreements and develops a generalized replenishment policy by taking into account the heterogeneity of the retailers. The meaning of homogeneity/heterogeneity of the retailers is dealt in detail in section 3.

2. Notations

Let i be the index for retailers, i =1,2….n, where n denotes the total number of retailers. For i^{th} retailer following notations are used :-

a_i Order cost for i^{th} retailer ($).

h_i Inventory carrying cost of i^{th} retailer ($/unit/unit time).

D_i Annual demand for the i^{th} retailer (Assumed to be deterministic in nature).

U_i Upper limit set by the retailer.

P_i Penalty imposed by i^{th} retailer for exceeding the upper limit U_i ($/unit).

X_i Quantity by which the upper limit is exceeded for i^{th} retailer.

Y_i Quantity by which the replenishment is under the upper limit for ith retailer.

For the supplier following notations are used :-

A Supplier setup cost ($).

D Annual demand for the supplier ($\sum D_i$).

h_s Inventory carrying cost of the supplier ($/unit/unit time).

Decision variables in the model are mentioned below :-

T Supplier setup cycle.

T_i ith retailer replenishment cycle

m_i Integer variable for ith retailer.

b_i Binary variable for ith retailer.

3. *Cycle ratio* and its role in generalized model

The role of the ratio "*setup cost/holding cost * demand*" in devising the optimal replenishment policy under a VMI context has been introduced in an earlier work by Verma et al. (2014). In this paper we define it as *cycle ratio* and elaborate on its role in developing the generalized model.

To understand *cycle ratio* we start by considering retailers and suppliers to be two independent entities. In such a scenario, retailer and supplier tries to replenish optimally by considering their EOQ(economic order quantity). The replenishment cycle then is *EOQ/Demand* i.e.,

Replenishment cycle = *EOQ/Demand* $\propto$ *setup cost/holding cost * demand*

Cycle ratio thus, gives us idea about the optimal replenishment cycle for the retailers and the optimal setup cycle for the supplier. To conceptually understand the problem under consideration we can therefore safely assume the ratio of optimal replenishment cycles T_i for the retailers to be in proportion to the ratio of their *cycle ratio* a_i/D_ih_i itself. Similarly, we can replace the optimal setup cycle T for the supplier with its *cycle ratio* A/Dh_s.

Let the retailers be divided into two sets viz. S_a and S_b. S_a is defined as the set of all the retailers with their respective optimal replenishment cycle T_i being greater than or equal to the optimal setup cycle of the supplier(T). S_b, on the other hand is defined as the set of all the retailers with their respective optimal replenishment cycle T_i being less than the optimal setup cycle of the supplier(T).

S_a – Set of retailers with $T_i \geq T$

S_b – Set of retailers with $T_i < T$

Thus, in the context of single supplier – multiple retailer scenario, three cases arise as stated below :-

Case 1 : When all the retailers belong to the set S_b (Figure 1).

Case 2 : When all the retailers belong to the set S_a (Figure 2).

Case 3 : When some retailers belong to the set S_b and some to the set S_a (Figure 3).

The diagrammatic representation for each of these cases are shown below :-

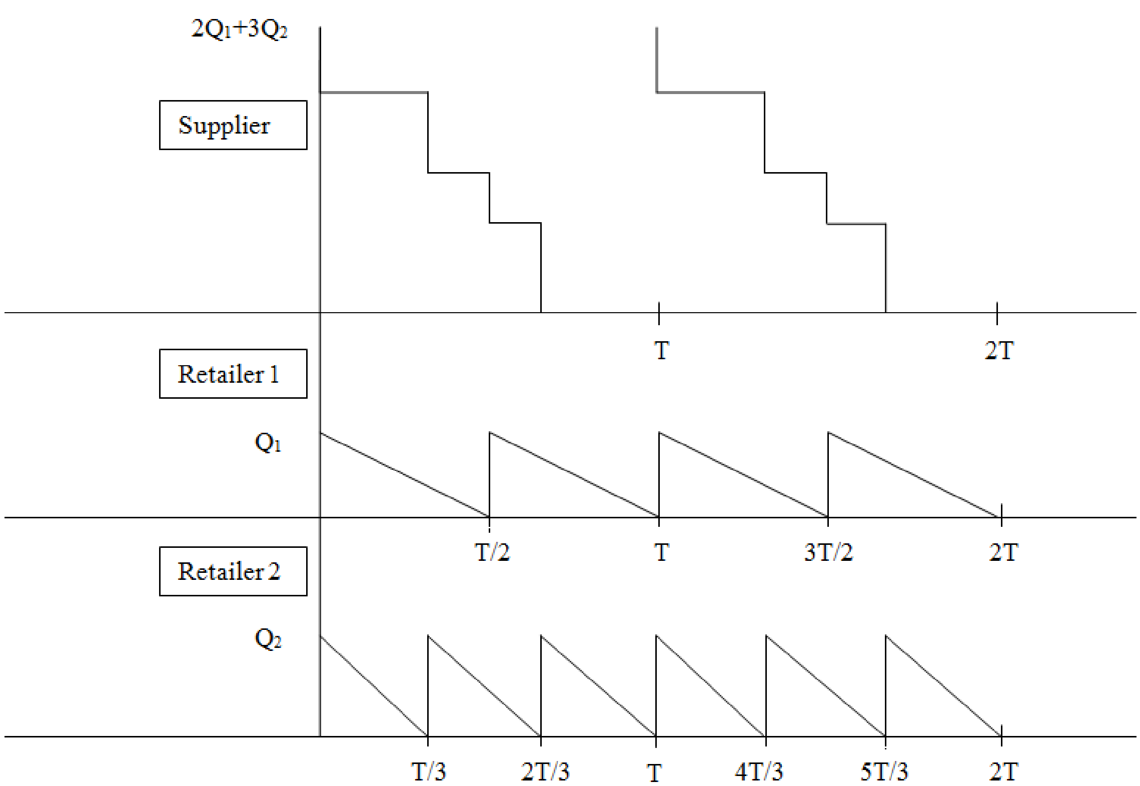

Figure 1. Diagrammatic representation of case 1, where both the retailers have T_i less than T viz. $T/2$ and $T/3$.

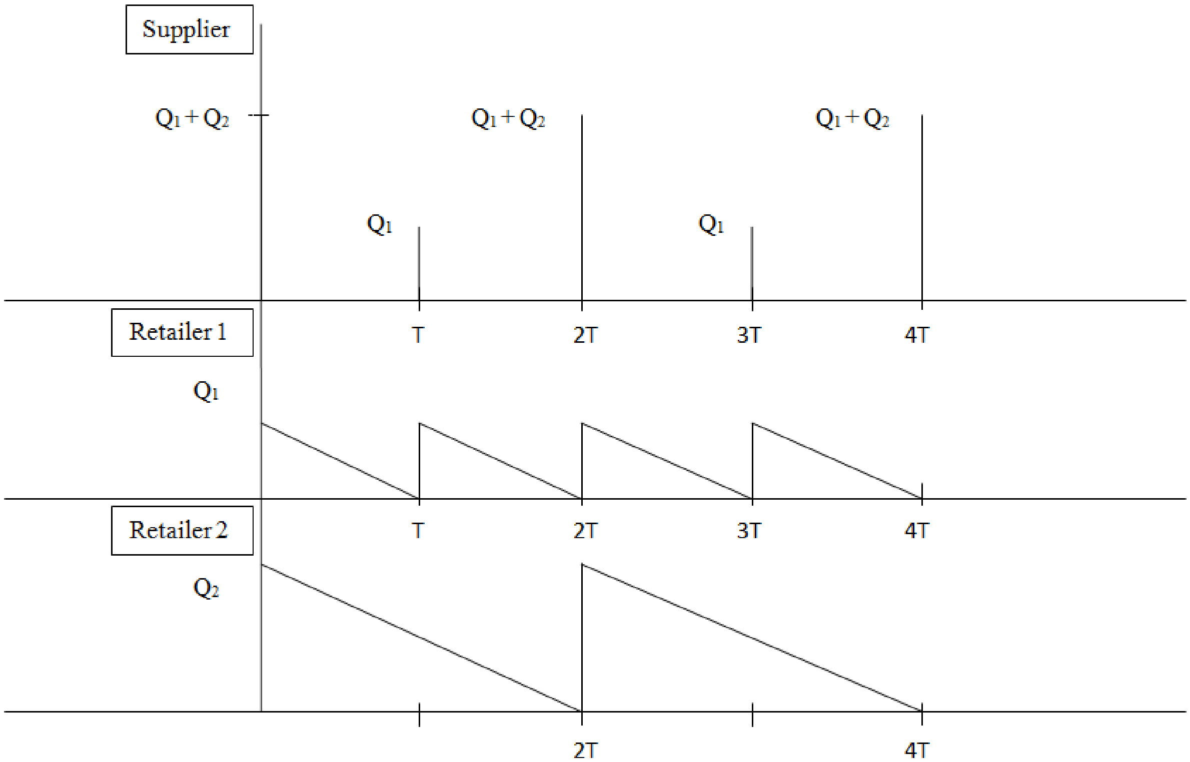

Figure 2. Diagrammatic representation of case 2, where both the retailers have T_i greater than or equal to T viz. T and $2T$.

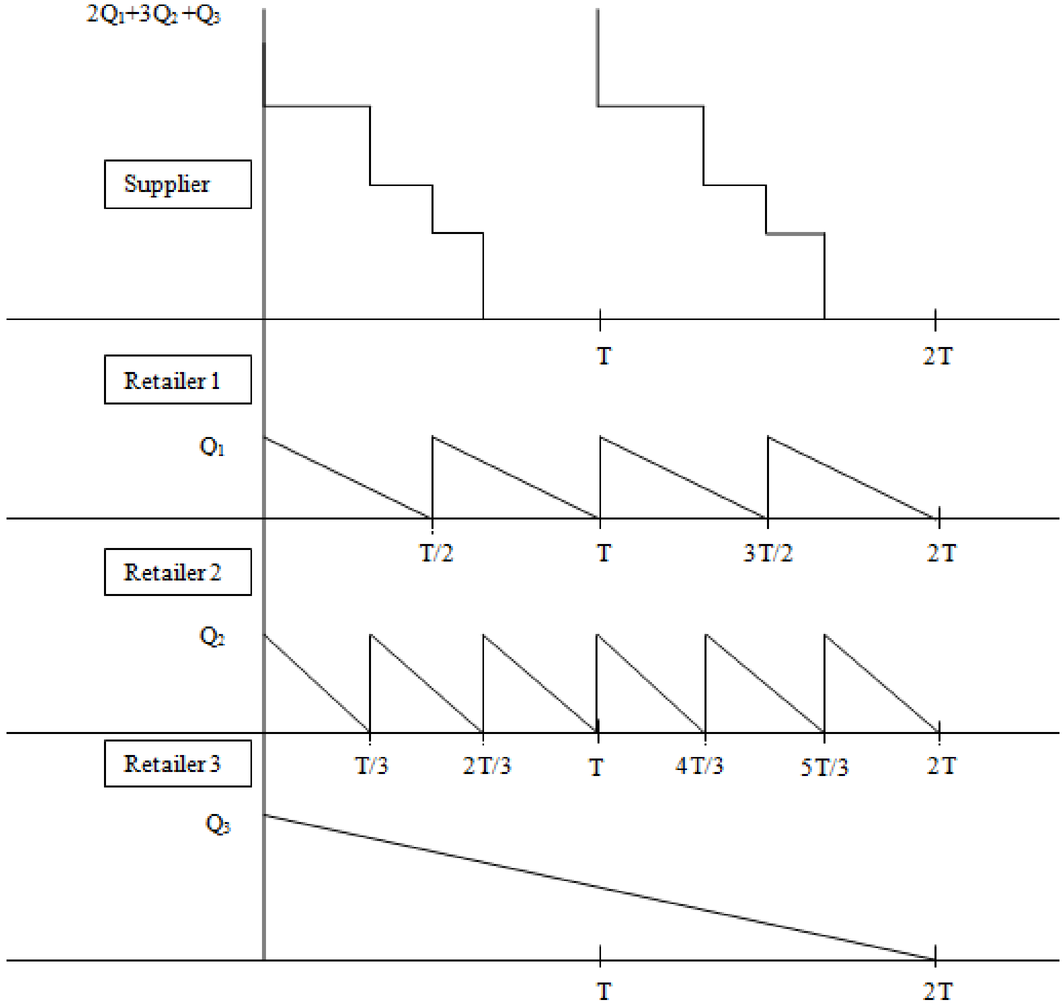

Figure 3. Diagrammatic representation of case 3, where two retailers have T_i less than T viz. *T/2* and *T/3* and one retailer has T_i greater than T viz. *2T*.

The ERI replenishment policies (Darwish & Odah, 2010) are always suboptimal as compared to the URI policies (Hariga et al., 2013; Verma et al., 2013) and therefore in this paper we intend to compare various URI policies. As pointed out in section 1, the URI policies present in the literature have the inherent assumption of retailers being homogenous. This homogeneity in terms of the *cycle ratio* means that either all the retailers have their *cycle ratio* more than that of the supplier (Verma et al., 2013) or all of them has *cycle ratio* less than that of the supplier (Hariga et al., 2013). However, in real life, retailers are heterogeneous in nature. Even when setup cost and inventory holding cost are assumed constant for all the retailers, the sales ratio of the retailers vary upto as much as 1:93 (National retail federation, 2013) suggesting the heterogeneity among retailers (in terms of *cycle ratio*). In terms of the cases depicted above, case 1 and case 2 are a representation of homogenous retailers and case 3 is a representation of heterogeneous retailers.

In this regard replenishment policy suggested by Hariga et al.(2013) is a representation of case 1 (depicted in figure 1) and that by Verma et al.(2013) is a representation of case 2 (depicted in figure 2). Replenishment policy by Hariga et al.(2013) does not cover case 2 and vice versa for the policy developed by Verma et al.(2013). Moreover, neither of these policies cover case 3.

The generalised policy developed in this paper covers all the three cases and therefore can be seen as a generalization of URI replenishment policies under VMI context. Thus the models suggested by Hariga et al.(2013) and Verma et al.(2013) will lead to suboptimal results in the presence of heterogeneous retailers. This is summarised in the table given below :-

ERI/URI	Policy	Case1	Case2	Case3
ERI	Darwish and Odah(2010)	Sub-Optimal	Sub-Optimal	Sub-Optimal
URI	Hariga et al.(2013)	Optimal	Sub-Optimal	Sub-Optimal
URI	Verma et al.(2013)	Sub-Optimal	Optimal	Sub-Optimal
URI	Generalized model	Optimal	Optimal	Optimal

Table 1: Conceptual comparison of various replenishment policies

4. Problem statement and model development

Consider a two echelon supply chain where supplier replenishes a common item to a number of retailers under a coordinating VMI contract. Under such a VMI contract the retailers provide their respective demand information to the supplier. The supplier after receiving the demand information sets-up every T period and replenishes i^{th} retailer every T_i period. Under such a VMI environment it is optimal for the supplier to push as much inventory as possible so as to save holding and transportation cost. To avoid such behaviour by supplier, the VMI contract imposes a condition wherein supplier incurs a per unit penalty cost P_i whenever the replenishment quantity exceeds the agreed upon upper limit of U_i (Fry et al., 2001; Shah & Goh, 2006).

Demands for the retailers are assumed to be deterministic in nature. Orders are replenished immediately to the retailers by the supplier i.e. zero lead time has been assumed. Also, the supplier in such a setting is assumed to have infinite capacity.

The model developed under such a VMI scenario seeks to minimize the total cost associated with this kind of two echelon supply chain. The total cost incurred by the supply chain is composed of retailer's cost and supplier's cost. Retailer's cost include ordering and inventory holding cost, whereas the supplier's cost include setup, inventory holding and penalty cost. The mathematical expressions for all the above stated components of total cost are mentioned below.

Cost components for i^{th} retailer :-

a_i / T_i	Ordering cost per unit time.
$.5 * D_i * T_i * h_i$	Inventory holding cost per unit time.

The total retailer cost TC_R is then the summation of above two components for all the retailers,

$$TC_R = \sum_i a_i / T_i + .5 * \sum_i D_i * T_i * h_i$$

Cost components for Supplier :-

A / T	Setup cost per unit time.
$.5 * h_s * \left(\sum_i (m_i - 1) * D_i * T_i * b_i \right)$	Inventory holding cost per unit time.
$.5 * \left(\sum_i (P_i / (T_i * D_i)) * X_i^2 \right)$	Total penalty cost incurred

The penalty expression for a single retailer can be visualized in figure 4 as shown below :-

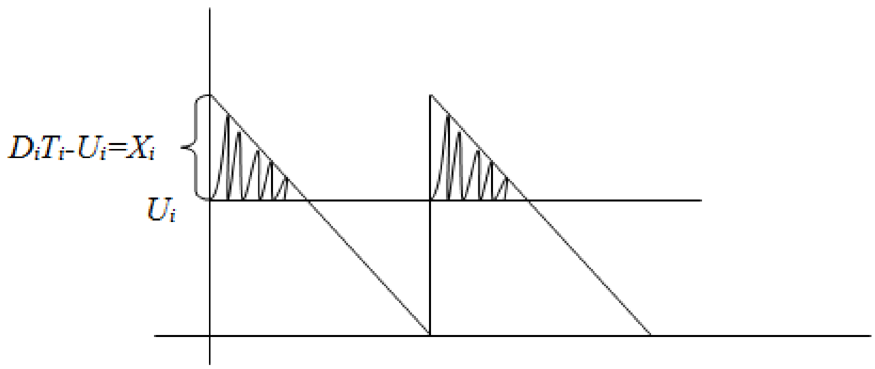

Figure 4. Diagrammatic representation of penalty cost.

The shaded portion is the penalty cost for the i_{th} retailer and can be written as $.5*(P_i / D_i)*X_i^2$. This when calculated per unit time and summed over all the retailers gives us the total penalty cost incurred.

The total supplier cost TC_S is then the summation of above three components,

$$TC_S = A/T + .5*h_s*\left(\sum_i (m_i - 1)*D_i*T_i*b_i\right) + .5*\left(\sum_i (P_i / (T_i*D_i))*X_i^2\right)$$

Now with the conceptual understanding of the replenishment policy and the various cost components we present below the mathematical model (objective function and constraints) :-

Minimize TC = $TC_R + TC_S$ =

$$A/T + \sum_i a_i / T_i + .5*\sum_i D_i*T_i*h_i + .5*h_s*\left(\sum_i (m_i - 1)*D_i*T_i*b_i\right) + .5*\left(\sum_i (P_i / (T_i*D_i))*X_i^2\right)$$

Subject To,

1. $D_i*T_i - U_i = X_i - Y_i \quad \forall i$
2. $T_i = (b_i / m_i)*T + (1 - b_i)*m_i*T \quad \forall i$
3. $b_i \le m_i - 1 \quad \forall i$
4. $\prod_i (1 - b_i)*(m_i - 1) = 0$
5. $m_i \ge 1 \quad \forall i$

6. $m_i \in I$ $\forall i$, I being set of all integers
7. X_i, Y_i ≥ 0; b_i – Binary $\forall i$

b_i is a binary variable with the following definition.

$b_i = 1$, if $T_i < T$
$b_i = 0$, if $T_i \geq T$

Constraint 1 gives us uniquely the amount by which replenishment quantity overshoots the upper limit for every retailer. As mentioned in section 2 every retailer is either a part of set S_a or a part of S_b. Constraint 2 ensures that a retailer is either in S_a (i.e. b_i =0 & T_i=m_i*T) or in S_b (i.e. b_i =1 & T_i=T/m_i). Retailers with m_i =1 i.e. T_i=T, are assumed to be part of set S_a and this is being ensured by constraint 3 wherein b_i is forced to take a value of 0 when m_i=1.

For situations where all the retailers are part of S_a (referred to as case 3 in previous section), at least one of them should have m_i=1. Constraint 4 ensures this condition.

Constraints 5,6,7 and 8 are trivial and follows from the definitions of the associated variables.

It is to be noted that supplier carries inventory only for the retailers having b_i = 1 i.e. for those whose T_i<T. The explanation for this can be carried out separately for the three possible cases as defined in previous section.

For case 1 wherein all the retailers have their respective T_i<T, the supplier carries inventory if it is optimal to do so.

For case 3 where some of the retailers have T_i<T and some have T_i>T, it is not optimal for the supplier to carry inventory for the retailers having b_i =0(i.e. for those having T_i>T). This is so because in such a case the supplier is going to setup every T period and therefore it is always suboptimal to carry inventory for retailers with b_i =0 or T_i>T or T_i=m_i*T.

For case 2 all the retailers have T_i>T, which in terms of *cycle ratio* means supplier's A/Dh_s is less than any of the retailer's a_iD_i/h_i . A/Dh_s is an indication of how frequently it is optimal for a supplier to setup which is very low for case 3 suggesting higher frequency of setups and less need of carrying any inventory. This is unlike case 1 where *cycle ratio* of the supplier is more than all of the retailer's *cycle ratio* and case 2 where it is more than at least one of the retailer's *cycle ratio*. Hence under case 3 the assumption of supplier not carrying inventory is justifiable.

The above model is solved using Global solver toolkit of optimization software Lingo 14.0. For the illustrative purpose we consider a VMI environment involving one supplier and six retailers with the input data as shown below:-

RETAILER DATA						
RETAILER	ANNUAL DEMAND	a_i	h_i	a_i/D_ih_i	Upper limit (U_i)	Penalty P_i (per extra unit)
R1	1000	60	10	.006	109.54	4
R2	700	60	5	.01714	129.61	3
R3	3000	70	14	.001667	173.2051	2
R4	2000	100	5	.01	282.8427	3
R5	3000	100	7	.00476	292.77	4
R6	4500	40	12	.000741	173.2051	3
SUPPLIER DATA						
Supplier		D	A	h_s	-	-
	Instance1	$\sum D_i = 14200$	450	5.5	-	-
	Instance2	$\sum D_i = 14200$	212	9	-	-
	Instance3	$\sum D_i = 14200$	300	7	-	-

Table 2: Data corresponding to the case of 1 supplier and 6 retailers.

We have considered three instances of supplier data such that each one when solved independently falls into one of the three possible cases discussed in section 2. All the three instances have also been solved for the replenishment policies suggested by Hariga et al.(2013) and Verma et al.(2013) which represents case 1 and case 2 respectively.

The results thus obtained are shown in the following tables below :-

Proposed Model	Total cost	R1	R2	R3	R4	R5	R6	Supplier
		m1/(S_a or S_b)	m2/(S_a or S_b)	m3/(S_a or S_b)	m4/(S_a or S_b)	m5/(S_a or S_b)	m6/(S_a or S_b)	T
Instance1	15016.46	1/ S_a	1/ S_a	2/ S_b	1/ S_a	1/ S_a	3/ S_b	0.13276
Instance2	13353.69	1/ S_a	2/ S_a	1/ S_a	2/ S_a	1/ S_a	1/ S_a	0.08123
Instance3	14106.41	1/ S_a	2/ S_a	1/ S_a	1/ S_a	1/ S_a	2/ S_b	0.10224

Table 3. Results for proposed generalised model.

Hariga et al.(2013)	Total cost	R1	R2	R3	R4	R5	R6	Supplier
		m1/(S_a or S_b)	m2/(S_a or S_b)	m3/(S_a or S_b)	m4/(S_a or S_b)	m5/(S_a or S_b)	m6/(S_a or S_b)	T
Instance1	15016.46	1/ S_a	1/ S_a	2/ S_b	1/ S_a	1/ S_a	3/ S_b	0.13276
Instance2	13577.57	1/ S_a	1/ S_a	1/ S_a	1/ S_a	1/ S_a	2/ S_b	0.09851
Instance3	14191.15	1/ S_a	1/ S_a	2/ S_b	1/ S_a	1/ S_a	2/ S_b	0.11533

Table 4. Results for policy suggested by Hariga et al.(2013).

Verma et al.(2013)	Total cost	R1	R2	R3	R4	R5	R6	Supplier
		m1/(S_a or S_b)	m2/(S_a or S_b)	m3/(S_a or S_b)	m4/(S_a or S_b)	m5/(S_a or S_b)	m6/(S_a or S_b)	T
Instance1	16004.57	1/ S_a	2/ S_a	1/ S_a	1/ S_a	1/ S_a	1/ S_a	0.10256
Instance2	13353.69	1/ S_a	2/ S_a	1/ S_a	2/ S_a	1/ S_a	1/ S_a	0.08123
Instance3	14400.65	1/ S_a	2/ S_a	1/ S_a	2/ S_a	1/ S_a	1/ S_a	0.08687

Table 5. Results for policy suggested by Verma et al.(2013).

The results shown in table 3,4 &5 include the total cost incurred by the VMI system, reorder cycle time for the supplier and the variable m_i associated with the retailers. The tables also include whether retailers belong to S_a or S_b. The replenishment cycle time for the retailers can be calculated as T/m_i if the retailer belongs to set S_b, or as $T*m_i$ if it belongs to set S_a. Other terms such as retailer cost, supplier cost etc can be calculated by using the expressions as defined in the model depicted above.

It can be observed that the results obtained for the above example are in accordance with the conceptual comparison made in table 2. The proposed model gives us the lowest cost for all the three instances as compared to other two models.

To bring out the comparison more clearly a number of instances were generated such that the supplier's *cycle ratio* was varied from a value less than any of the retailer's *cycle ratio* to a value more than any of the retailer's *cycle ratio*. A graph depicting the comparison between the three models in terms of total cost is shown below (Figure 5):-

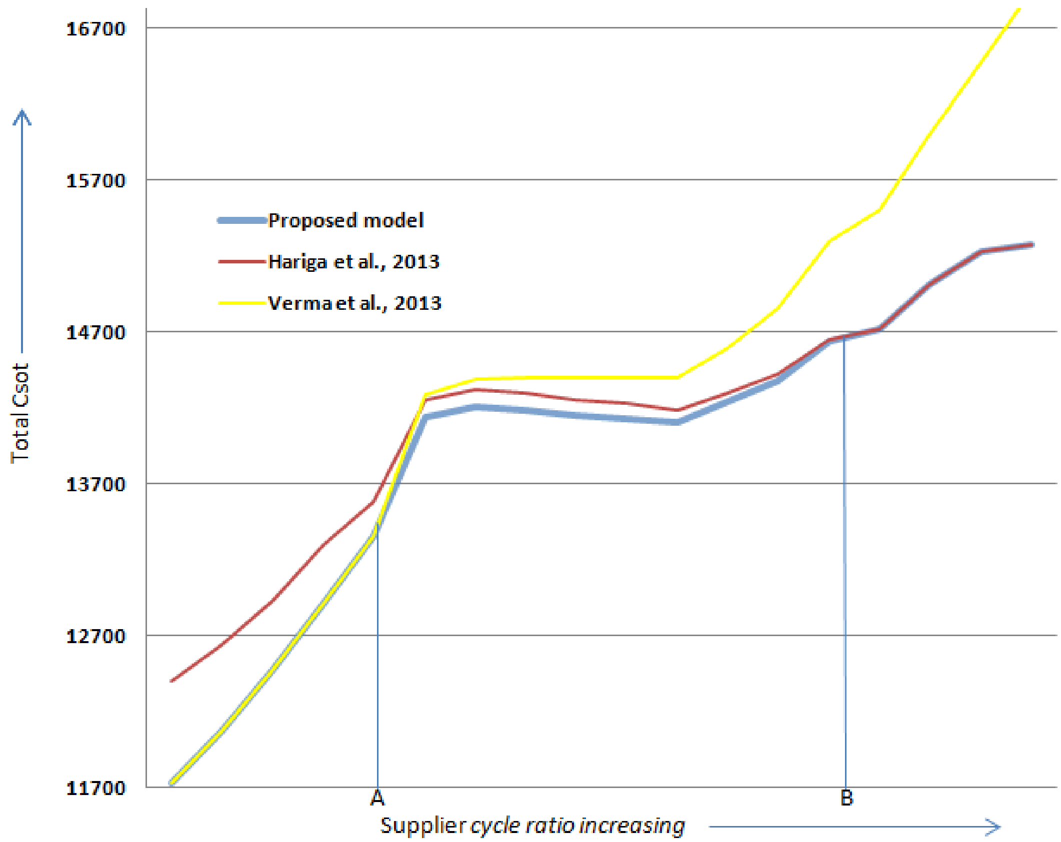

Figure 5. Total cost comparison of the three types of replenishment policies.

It has clearly come out in the graph that the proposed model has the lowest cost among the three models for all the instances. Also, below point A i.e. when the supplier's cycle ratio is too low as compared to the retailer's, model by Verma et al.(2013) performs better than the model by Hariga et al.(2013) and vice versa for the instances above point B. Moreover, the limitation of existing models in the scenarios of heterogeneous retailers has come out clearly in figure 5.

5. Conclusion

In this paper we have developed a generalized model under the contractual VMI setup for the replenishment of multiple retailers. In practice, in a multi retailer setting, retailers can be heterogeneous in nature with respect to their *cycle ratio*. Considering this we have tried to show, how the proposed model gives the optimum result vis a vis the existing models.

With the help of an example we have compared the existing models with the proposed model to show how the proposed model achieves the lowest total cost as compared to the other models. All the three models including the proposed model have been solved for a number of instances to clearly show how each of the models behaves under different scenarios.

The supplier in the VMI setup for multiple retailers is in advantageous position as it is the only entity with complete information. Thus, the future course of research could be to study the impact on individual retailer's cost when the supplier chooses to optimize its cost independently instead of minimizing the cost of total supply chain.

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