Up-to-Date Supply Chain Management: The Coordinated (S, R) Order-Up-to

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Abstract. This paper presents the mathematical derivation of a new generation of the most largely used periodic review policy in supply chain: the coordinated (S, R) replenishment rule. We first derive the classical order-up-to model and then we modify it to generate the coordinated decision policy equations. We run a numerical simulation on a serial supply chain model to show differences in the two policies. We conclude on the managerial implications related to coordinated replenishment.

Keywords: multi-echelon; production and inventory management; information sharing; collaboration; synchronization of operations; decision policy; OUT; bullwhip effect.

1 Prologue

In the last decades large-scale collaboration projects have gradually modified the *modus operandi* of global supply chains partners. Efficient consumer response [1], Vendor Managed Inventory (VMI) [2], [3], continuous replenishment [4], collaborative planning, forecasting and replenishment [5], [6], and centralised inventory management [7], have reshaped material and information flows, intensified alliances and transformed strategies, organisations and corporate culture [8]. These structural changes have modified the nature of production planning and control and, more specifically, the dynamics of one of its main objectives: the decision on the order quantity. Real-time sharing of market demand data for the generation of conjoint forecasts and sharing of information on inventory levels and in-transit items for centralised replenishment pushed towards the generation of novel order policies that enable fully coordinated decision-making approach in supply chain. The mathematical formalization of VMI collaboration practices [9], [10], the object-oriented and spreadsheet simulation models of the Electronic Point Of Sales supply chain [11]-[13], the classification framework on the degree of synchronisation of members' operations [14], [15], novel designs of order policies for flexible capacity [16], [17], form a non-exhaustive list of cornerstone publications that prove: *(1)* how classical inventory management policies have definitively evolved to adapt to the increasing proliferation of ICT in logistics

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operations, *(2)* that formalisation, modelling and clarification of the new coordinated decision-making mechanisms is one of the current paradigms in supply chain management[1].

In this paper we present the evolution of the most largely used periodic review policy [19]-[21] for a make-to-stock multi-echelon supply chain: the (S, R) order-up-to. We first derive the order policy for a traditional serially linked multi-echelon system and then, on the basis of the classical (S, R) archetype, we generate an order-up-to policy for a coordinated multi-echelon supply chain. To undertake our mathematical derivation, we adopt the classical analytical modelling approach for production inventory control [22]-[24]. We run a numerical simulation on a serial supply chain model to show differences in performance of the two policies. We conclude discussing on the benefits deriving from shifting from a classical (S, R) to a coordinated (S, R).

2 Classical (S, R) Policy

Table 1. Notation

W	work in progress	d	customer demand
I	inventory of finished materials	$\hat{d}$	customer demand forecast
O	replenishment order quantity for the classical (S, R)	α	demand smoothing forecasting factor
O'	replenishment order quantity for the coordinated (S, R)	TI	target inventory
C	units finally delivered	TW	target work in progress
λ	production-distribution lead time	I'	multi-echelon inventory
ε	safety stock factor	W'	multi-echelon work in progress
λ'	multi-echelon production-distribution lead time	TI'	multi-echelon target inventory
ε'	multi-echelon safety stock factor	TW'	multi-echelon target work in progress

The classical (S, R) order quantity for a generic echelon is first derived for a traditional multi-echelon model under the following assumptions:

- K-stage production-distribution serial system. Each echelon in the system has a single successor and a single predecessor (Figure1).
- The generic echelon's position is represented by index *i*. Echelon *i*=1 stands for the manufacturer and *i*=K+1 for the final customer.
- Single product. Aggregate production plans are assumed.

[1] Until recently, many firms regarded their knowledge base as a proprietary asset and they hesitated to share it for confidentiality reasons. Established process and models illustrating the positive benefits to information sharing and coordination will help companies to change their attitude towards information integration, meaningfully sharing data and utilising supply chain partners' knowledge [18].

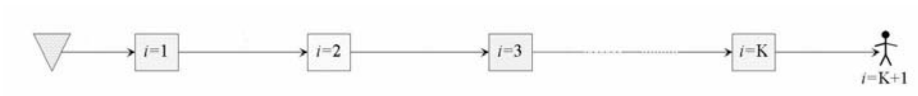

Fig. 1. Serial Multi-echelon supply chain

In the classical (S, R) rule, in a multi-echelon system a generic tier bases its replenishment decision on local information and the order coming from the adjacent downstream echelon. At each review time R, a quantity O is ordered to bring the level of the available inventory up to a level S. The order-up-to order quantity for a generic echelon i is given by eq. 1.

$$O(t) = S(t) - inventory\ \ position\,. \tag{1}$$

The S level for a generic echelon i (eq. 2) is equal to the forecast on the order O_i coming from the subsequent echelon i+1 during the review period R, plus the forecast on the order from echelon i+1 during the production-delivery lead time λ_i, plus a safety stock to prevent shortages. The safety stock depends on a factor ε_i and it is expected to provide sufficient stock to prevent a possible stock-out during the lead time λ_i plus the review period R [20].

$$S_i = R_i\hat{O}_{i+1} + \lambda_i\hat{O}_{i+1} + \varepsilon_i\hat{O}_{i+1}\,. \tag{2}$$

The inventory position (eq. 3) is given by inventory on hand I_i plus pipeline inventory or work in progress W_i (wip).

$$inventory\ \ position_i = I_i + W_i\,. \tag{3}$$

The order quantity for echelon i is herein derived for R=1 (eq. 4, eq. 5 and eq. 6).

$$O_i = \hat{O}_{i+1} + \lambda_i\hat{O}_{i+1} + \varepsilon_i\hat{O}_{i+1} - I_i - W_i\,. \tag{4}$$

$$O_i = \hat{O}_{i+1} + (\varepsilon_i\hat{O}_{i+1} - I_i) + (\lambda_i\hat{O}_{i+1} - W_i)\,. \tag{5}$$

$$O_i = \hat{O}_{i+1} + (TI_i - I_i) + (TW_i - W_i)\,. \tag{6}$$

According to Disney and Lambrecht [20], the safety stock $\varepsilon_i\hat{O}_{i+1}$ can be viewed as a target net stock TI_i and the quantity $\lambda_i\hat{O}_{i+1}$ as a target pipeline stock or target work in progress TW_i

From eq. 4-6 it is possible to identify that, in order to generate an order-up-to level in a traditional production-distribution system, the data to be gathered are: local inventory level, local work in progress level, downstream incoming orders, safety stock factor and lead time. To conclude, the classical order-up-to is composed by three terms: (1) forecast on the order from the subsequent echelon i (2) work in progress gap (3) inventory gap.

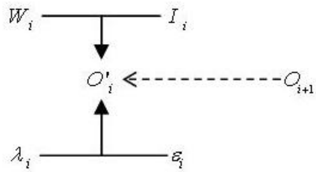

Fig. 2. Operational information for the classical (S, R)

Figure 2 summarises the information used by an echelon to generate the order quantity with the classical (S, R) policy.

In the following section we show how the three terms of the classical (S, R) modify when information is shared among partners and operations are coordinated.

3 Coordinated (S, R) Policy

The coordinated decision-making in the multi-echelon supply chain is modelled under the same conditions of the previous model. Furthermore, the following two relevant assumptions are considered:

- Market demand is visible to all echelons. All echelons adopt the exponential smoothing rule to forecast demand.
- A generic echelon i receives information about order quantity O'_{i+1} from the downstream adjacent echelon $i+1$, as in the classical (S, R) order-up-to, plus information on the up-to-date market demand d and on safety stock factors ε_j, lead times λ_j, inventory levels I_j, and work in progress levels W_j from all downstream echelons $j=i+1\ldots K$.

First of all we underline that in the coordinated (S, R) policy, unlike the classical policy, the aim of a generic tier is not to serve the order generated by the subsequent adjacent stage, but the demand coming from market. This implies that the risk period (lead time plus review period) has to be referred to the entire time length needed to deliver the finished product from the generic tier to the final customer. According to Clark and Scarf's multi-echelon model [25], recognised as the seminal work in multi-echelon inventory analysis [26]-[29], in the determination of the replenishment quantity any echelon needs to consider its successors as a part of its inventory system.

Maintaining the same formalism as in the classical (S, R), we derive the formula for the coordinated order-up-to level S'. The S' level for a generic echelon i (eq. 7) is equal to the forecast of customer demand d during the review period R, plus the expected customer demand during the multi-echelon lead time λ_i', plus the multi-echelon safety stock to prevent shortages.

$$S_i' = \lambda_i'\hat{d} + R_i\hat{d} + \varepsilon_i'\hat{d} \ . \tag{7}$$

The multi-echelon lead time *λ'* for echelon *i* is the entire time period needed to deliver the finished product from the generic tier to the final customer (eq. 8).

$$\lambda_i' = \sum_{j=i}^{K} \lambda_j \,. \tag{8}$$

Analogously, the multi-echelon safety stock factor *ε'* from echelon *i* to customer K+1 is given by eq. 9.

$$\varepsilon_i' = \sum_{j=i}^{K} \varepsilon_j \,. \tag{9}$$

The inventory position at echelon *i* (eq. 10) is given by the multi-echelon inventory I_i' (eq. 11) plus the multi-echelon pipeline inventory or multi-echelon work in progress W_i' (eq. 12).

$$inventory\ \ position_i' = I_i' + W_i' \,. \tag{10}$$

$$I_i' = \sum_{j=i}^{K} I_j \,. \tag{11}$$

$$W_i' = \sum_{j=i}^{K} W_j \,. \tag{12}$$

The multi-echelon inventory I_i' is the sum of the inventory levels I_j from echelon *i* to echelon K (inventory level at echelon i plus inventories levels of all downstream echelons *j*=*i*+1…K). The multi-echelon work in progress W_i' is the sum of the work in progress levels W_j from echelon *i* to echelon K (work in progress at echelon *i* plus work in progress of all downstream echelons *j*=*i*+1…K).

Such as the classical (S, R), the order quantity *O'* is derived for R=1 (eq. 13, eq. 14 and eq. 15). Analogously to the previous configuration, the term $\varepsilon_i'\hat{d}$ can be viewed as a multi-echelon target net stock TI_i' and the term $\lambda_i'\hat{d}$ as a multi-echelon target pipeline stock or multi-echelon target work in progress TW_i'.

$$O_i' = \lambda_i'\hat{d} + \hat{d} + \varepsilon_i'\hat{d} - I_i' - W_i' \,. \tag{13}$$

$$O_i' = \hat{d} + (\varepsilon_i'\hat{d} - I_i') + (\lambda_i'\hat{d} - W_i') \,. \tag{14}$$

$$O_i' = \hat{d} + (TI_i' - I_i') + (TW_i' - W_i') \,. \tag{15}$$

The main difference between a classical (S, R) and a coordinated (S, R) can be inferred from the comparison of eq. 4-6 and eq. 13-15. In the classical (S, R) the determination of order quantity is based on the order quantity placed by downstream adjacent echelon. In the coordinated (S, R) the determination of order quantity is based on the market demand and the inventory levels and in-transit items from all downstream echelons. Figure 3 summarises the information used by a generic echelon to generate a coordinated order quantity.

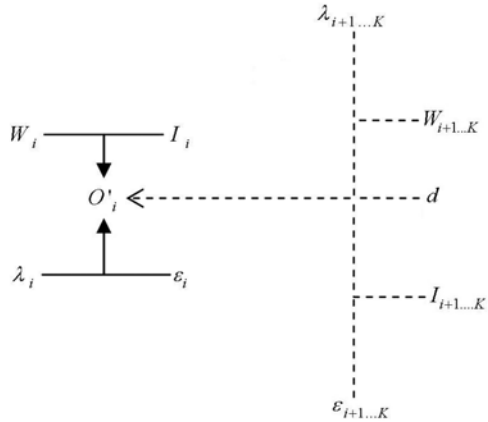

Fig. 3. Operational information for the coordinated (S, R)

4 Numerical Example

We now show a numerical example to highlight the different performance of the classical (S, R) policy and the coordinated (S, R) policy. In our example the two decision rules are adopted in a serial supply chain system.

The two decision rules are compared in terms of demand amplification and inventory stability, with two referenced metrics: Order Rate Variance Ratio [30] and Inventory Variance Ratio [10].

The presented model follows Sterman's traditional supply chain order of events [31]. Refer to [8] for details on the model. To set the numerical values for the experiment, we refer to contributions validated in the literature. The lead time and demand smoothing forecasting factor, the initial values of the state variables, safety stock factor, and the market demand pattern refer to the setting of Sterman's traditional supply chain model [31] and also used in Wikner et al. [32], Van Ackere et al. [33], John et al. [34], Crespo Márquez et al. [35], Machuca and Barajas [36], Jakšič and Rusjan [37], and Wright and Yuan [38].

The numerical experiments are performed under the following settings:

- The serial system is composed by K=4 echelons.
- Supply chain member adopt exponential smoothing to forecast customer demand and incoming orders.
- The initial values of the state variables are: $[W_i(0), I_i(0)]=[\lambda_i d(0), \varepsilon_i d(0)]$
- The lead time is equal to 3, demand smoothing forecasting factor is equal to 0.33 and safety stock factor is equal to 3.
- Numerical experiments are performed for a time length T=52.
- The solutions for the initial-value problem are approximated through Vensim PLE. The Euler-Cauchy method with order of accuracy $\Delta t = 0.25$ is adopted.
- The market demand *d* is initialised at 4 units per time unit, until there is a pulse at t=5, increasing the demand value up to 8 units per time unit.

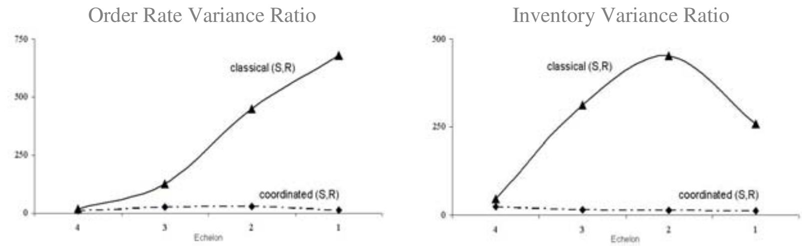

Fig. 4. Order Rate Variance Ratio and Inventory Variance Ratio for classical (S, R) and coordinated (S, R)

Figure 4 reports Order Rate Variance Ratio and Inventory Variance Ratio for classical (S, R) and coordinated (S, R) according to Dejonckheere et al.'s notation [39]. Echelon i=1 stands for the manufacturer and i=4 for the retailer.

The numerical example shows how the classical (S, R) exhibits a geometrical increase of order variance in up-stream direction (from retailer to manufacturer) and high inventory variability. On the contrary, under the same parameter setting, the coordinated (S, R) policy stabilises inventory and significantly avoids demand amplification phenomenon. On the basis of the adopted metrics, it is shown that the coordinated (S, R) largely outperforms the classical order-up-to policy. More specifically, the significant reduction of Order Rate Variance Ratio shows how shifting from classical (S, R) to a coordinated (S, R) results in a reduction of several production and distribution costs [37], [39]. Analogously, the reduction of Inventory Variance Ratio reflects lower holding and backlog costs, drastically diminishing the average inventory cost per period [17], [38].

5 Managerial Implications of Coordinated (S, R)

During the last decade, several companies adopted large-scale collaboration projects such as VMI. The implantation of this typology of collaboration practices between supplier and retailer have often exclusively modified the ownership of the inventory, without changing how the replenishment orders are generated with respect to a traditional system.

As reported by Holweg et al. [14], the retailer can and does pass sell-through data and inventory levels to the manufacturers' plants. The supplier exploits this information implicitly in strategic planning issues, such as capacity planning and manning levels in the factory, but very often she does not exploit the consumption information at a tactical planning level. In other words, supply chain members do not fully benefit from the shared operational information for the generation of a coordinated decision order. Case studies show how this VMI arrangement can degenerate in five-to-one increase in the bullwhip effect at each level of the supply chain [14]. Counter to the common perception, several VMI supply chains remain, from the operational perspective, mere traditional structures [14]. As a consequence, several companies did not succeed in eliminating inefficiencies such as demand amplification. It was largely shown in the literature that the classical (S, R) is by nature extremely prone to demand amplification phenomenon generation, whatever forecasting method is used [40]. On the contrary, it was shown that coordinated order decision making can allow elimination of bullwhip [41]-[43], reduction of inventory levels [44], better utilisation on transportation resources [45], controlling the risk for constrained components of material [46], [47].

In this paper we showed how adopting a collaboration system based on the coordination of operations leads to performance improvement and creates a win-win solution for all supply chain partners.

To conclude, the coordinated (S, R) represents a relatively simple solution to several inefficiencies in supply chain. Its implementation in the large-scale collaboration practices represents a concrete mean to achieve the recently advocated improvements in supply chain operations.

6 Conclusion and New Directions in Coordinated Policies

This paper presented the mathematical derivation of a new generation of the most largely used periodic review policy in supply chain: the coordinated (S, R) replenishment rule. We first derived the classical order-up-to model and then we modified it to generate the coordinated decision policy. We concluded on the managerial implications related to the implementation of the coordinated (S, R) order-up-to.

Even more supply chain collaboration models and practices appear in literature and practices. One of the novel examples is the global inventory policy for a two echelon supply chain discussed by Gaalman and Disney [48]: go-policy. This policy is like a VMI supply chain in reverse. The innovation of this policy stands in a feedback mechanism that corrects some of the manufacturer's forecast errors with the support of retailer. The realisation of new coordination order policies converts day-by-day in a tangible possibility. This is due to the recent advances of ICT and the related decreasing of the controlling inventory costs. However, in the future decade, researchers and practitioners should focus and overcome one of the real problems (rarely addressed in operation management literature) to concretise the operational collaboration: the reluctance of the companies to share with their partners/competitors operational information regarding their own core business.

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