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Coordination in Supply Chains Using Vendor Managed Inventory: How to Balance the Risks of Uncertainty?

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Abstract: This paper exposes the problem of coordinating a supply chain by the vendor managed inventory (VMI) method in face of uncertain demand. By applying mechanism design theory, we analyze strategic interactions of self-interested partners who have private information about demand forecasts and cost factors, respectively. After showing that in a practical setting no contract can guarantee a given profit sharing rate, we present a VMI service model that is efficient and compensates the supplier for its increased inventory risk. Some aspects of this model are discussed with reference to a running application.

Keywords: Flexible supply, Vendor managed inventory, Cost and risk management

1 Introduction

In the past decades the circumstances of industrial production dramatically changed: increasing customer expectations require ever shorter delivery times, customized products and extremely high service levels. Besides the traditional problem of the uncertain demand, recent paradigms – such as mass customization, short product life-cycles, delayed differentiation, outsourcing – , and the increasing incidence of networked production systems necessitate novel models and solutions for the production and logistic processes (Jovane, *et al*., 2009). The different steps of production – like manufacture of components, assembly, etc. – are usually carried out by *autonomous* and self-interested enterprises that are linked by supply chains. Similarly to the well known prisoner's dilemma, disparate objectives and

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the decentralization of decisions result typically in suboptimal overall system performance, a phenomenon called *double marginalization* in microeconomics. Hence, decentralized decision making often leads to inefficient production, resulting in waste of materials, labor, energy, environmental resources, eventually causing significant financial losses for the enterprises. The relatively new theory of *channel coordination* aims at avoiding or dampening this effect, and developing arrangements for aligning the different objectives of the partners (Arshinder, *et al.*, 2008). For some specific customer-supplier relations and market conditions, appropriate channel coordination methods induce autonomous partners to act as if they were forming a vertically integrated virtual enterprise. Such examples are the *quantity discount contract*, the *buyback/return contract* and the application of *revenue sharing agreements* instead of fixed prices (Tang 2006; Kouvelis, *et al*., 2006). Winkler*, et al.*, (2008) present that the coordination approach can be successfully applied also in project-oriented supply networks.

One of the most widespread practical business models aimed at coordinating decisions in vertically integrated, long-term supply relations is the *vendor managed inventory* (VMI). The bottom of this approach is that the customer delegates the ordering and replenishment planning to its supplier. Having received some information about the demand forecast from the customer, the supplier is responsible for managing the inventory and fulfilling actual demand in a flexible way. According to Tempelmeier (2006), the rationale behind this setting is that it is in fact the supplier who can control the actual production and logistic cost, who can decide on the optimal production and transportation lots, as well as the balanced utilization of resources. At the same time, this means also that mainly the supplier faces the consequences of imprecise forecasts.

Forecasts are, however, by definition uncertain. The key issue we investigate in this paper is how to balance the *risk of uncertainty*. Given an inherently *asymmetric* situation – where the customer knows (rather guesses) the demand forecast, while the supplier knows the various cost factors – is it possible to coordinate the channel to the benefit of both partners? Are there any ways to drive the customer to make and communicate as precise forecasts as possible? The pragmatic managerial approach to tackle uncertainty is (re-)planning time and again on a rolling horizon; is there any business model that fits this well-proven decision making practice? Coordinating supply on a rolling horizon has recently been studied by Lian and Deshmukh (2009), but they consider firmed orders instead of the VMI approach, where the flexibility means that the customer can always *add* new orders, but cannot withdraw previous ones.

We base our analysis and answers on results of *mechanism design* (MD), a subfield of microeconomics that, according to Nisan (2007), has a specific engineering perspective. MD borrowed key concepts of game theory, like *strategies*, *equilibrium* and *rationality*, but instead of being interested in the output of a given game, it aims at determining the *rules* of the game in order to achieve certain behaviors. Accordingly, MD can resolve dilemmas and suboptimal performance in strategic situation by aligning the objectives of the players. The founders of the theory were recently awarded with Nobel prize, and it has already been successfully applied in designing and analyzing practical auction mechanisms for electronic markets. Since this theory considers strategic interactions of self-interested agents with incomplete (private) information, it offers promising applicability also in supply chain research. To the best of our knowledge, the use of mechanism design concepts in this field is a novelty.

In what follows, we present an analysis of the VMI supply, considering a practical setting and requirements suggested by the industrial partners of our recent research project. After presenting general results of a theoretical analysis, we describe also a coordination scheme and give a summary of large-scale simulation experiments. Finally conclusions are drawn and the generalization of our approach towards other customer-supplier relation types is suggested.

2 Theoretical Background

2.1 Assumptions on VMI Supply

In a VMI model, the buyer of a product should provide forecasts to a supplier about the expected demand of that product. The supplier takes full responsibility for maintaining an agreed inventory, usually at the buyer's premises. Thanks to information sharing and appropriate assignment of responsibilities, VMI holds the promises of reducing both stock-outs and inventories in a given supply chain. The particular model we deal with in this paper has the following main properties:

- *Vertically integrated two echelon supply chain*. We consider a customer and a supplier working together on the long run. Hence, the partners can exchange information, products and payment on a regular basis. The plans cover a fixed length horizon, and are updated from time to time in a rolling horizion manner. The manufacturer of end products – so-called Original Equipment Manufacturer (OEM) – is considered to be in the customer's role, who receives component supply from its partner.
- *VMI supply*. We assume that the supplier decides about the component production, inventory and logistic plans. For supporting the supplier's decision making, the customer should share the demand-related information with the supplier. This situation causes two practical problems: (i) the customer is not interested in improving the precision of the forecasts, and (ii) the entire inventory risk raises at the supplier.
- *100% service level*. The single criteria towards the supplier is that the actual demand must be fulfilled at the highest possible service level, even if this necessitates costly production – e.g., overtime or outsourcing.
- *Asymmetric information*. We consider asymmetric and incomplete information, i.e., only the supplier knows the cost parameters of the component production, while the customer is familiar with the demand forecasts. In addition, *strict incomplete information* is allowed, i.e., the partners do not necessarily have beliefs about each others' private information.
- *Commonly known realised demand*. We assume that the finally realised demand is known also by the supplier.

2.2 A Mechanism Design Model for VMI

Firstly, the above situation is formulated as a generic MD problem, which necessitates an independent *third party*, whom the players share their information, and who decides about the production plan. Later it will be shown that the central party can be omitted, thus the results of the theoretic analysis also hold in the practical situation. Let θ denote the component *forecast* and c the *cost function* of the supplier. Note that in this general model we do not restrict the domain of these parameters, thus the forecast may have any complex structure with multiple periods and any additional information. Since these parameters are privately known, rational players may not share them truthfully, therefore we need to differentiate the communicated forecast and cost information with $\hat{\theta}$ and $\hat{c}$, respectively.

In the MD setting, the central party decides about the production by creating a *production plan* based on the forecast and the cost structure, denoted by $f(\hat{\theta},\hat{c})$. This general notation may again allow any optimization model and algorithm. The resulted production plan should be executed by the supplier. When the final demand ξ occurs, the customer pays $t_1(\hat{\theta},\hat{c},\xi)$ to the central planner, who pays $t_2(\hat{\theta},\hat{c},\xi)$ for the supplier. All in all, the profit of the customer becomes the income minus the payment: $v(\xi)-t_1(\hat{\theta},\hat{c},\xi)$, while the supplier's profit is the payment minus the cost: $t_2(\hat{\theta},\hat{c},\xi)-c(f(\hat{\theta},\hat{c}),\xi)$. Fig. 1 summarizes this model.

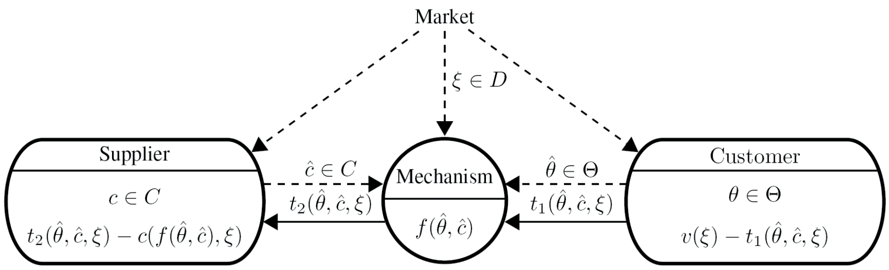

Fig. 1. Mechanism design setting

Given this general model, the behavior of the system ought to have the following properties:

- *Budget balance*. This means that $t_1 = t_2$. Without budget balance, the third party is inevitable in order to level off the difference between the two payments.
- *Strategy-proofness*. This property states that truthful information sharing is optimal for the partners, i.e., $\hat{\theta} = \theta$ and $\hat{c} = c$. Strategy-proofness can be required without loss of generality, according to the *revelation principle*, a main theorem of the MD theory, see e.g. Nisan (2007).
- *Efficiency*. This holds if the profit of the whole system defined by the income minus the cost is maximal. In our case, this means that the cost $c(f(\hat{\theta},\hat{c}),\xi)$ is minimal, since the income is independent from the decisions.
- *Cost and profit sharing*. Guaranteed rate from the total profit for the partners would imply their profitability. A more frequently regarded,

weaker form of this property called *individual rationality* requires only that the profit should be non-negative for both partners.

After investigating the requirements of these properties, we could prove analytically that *by demanding budget balance and efficiency, no contract can guarantee a given profit sharing rate* or individual rationality, regrettably. Due to the lack of space, we refer to Egri (2008), which contains the details of this theorem. Therefore, the idealistic goal of controlling the profit allocation between the partners in this setting is unattainable, which is an immanent property of the VMI with incomplete information, and not the imperfection of any practical or theoretical coordination scheme.

After pointing out this inherent limitation of VMI supply, we required only budget balance and efficiency. Instead of demanding a guaranteed profit sharing rate, only the *compensation* of the supplier for the increased inventory risks was aimed. In the next section, a compensation-based contract scheme is presented that fulfils these requirements, covering the practically widespread case of multi-period, rolling horizon planning. The proposed solution applies a compensation for imprecise forecasts, which inspires the customer (i) to make as good forecasts as possible, and (ii) to share them truthfully. Furthermore, the scheme is budget balanced, and since the supplier minimizes the cost, it can provide efficiency without any third party, which makes the approach applicable in practice.

3 A Service Model for Vendor Managed Inventory

Earlier, we developed a service model for VMI and an appropiate contract scheme for coordinating supply on a multi-period, rolling horizon (Váncza, *et al*., 2008). In the following, it is shown how this practical service model realizes an instance of the generic coordination mechanism presented above.

3.1 Compensating the Risk of Imprecise Multi-Period Forecasts

An *n*-period problem will be considered, where the forecast is $\theta = (\theta_1, \ldots, \theta_n)$, the vector of the expected demands, while the realized demand is $\xi = (\xi_1, \ldots, \xi_n)$. We derive a budget balanced ($t_1 = t_2$) compensation scheme, thus from now on the index of the payment function is omitted. In order to enable efficiency and strategy-proofness, we are looking for a payment which is independent from the supplier's cost (for an explanation see Egri (2008)). The payment is defined as $t(\hat{\theta}, \xi) = c_0 \sum_{i=1}^{n} \xi_i + c_1 d(\hat{\theta}, \xi)$, where c_0 is the unit price for the bought components, c_1 defines the rate of the compensation, and $d(\hat{\theta}, \xi)$ is some kind of metric, measuring the *imprecision of the forecast*. Practically, the first term can be considered as the payment for the supplied products, while the second one defines the price of the VMI service. Note that only the compensation depends on the shared forecast, therefore in order to assure truthfulness, it is sufficient to construct such an imprecision measurement, whereof the minimum is at $\hat{\theta} = \theta$. In Váncza, *et al.*, (2008), two different measurement functions were proposed:

$d_{MTO}(\hat{\theta},\xi)=\sum_{i=1}^{n}\left|\hat{\theta}_i-\xi_i\right|$, and $d_{MTS}(\hat{\theta},\xi)=\left|\sum_{i=1}^{n}\left(\hat{\theta}_i-\xi_i\right)\right|$. Note that although the imprecision can be calculated only in period n, when all of the realized demands are already known, it can be estimated in period k, ($k<n$) by letting i go from 1 to k, (instead of n).

Table 1 illustrates these two approaches with a very simple example. In this case, the demand of periods 1 and 3 are the same as the forecasts, while period 2 was over-, and period 4 was underestimated. If one considers the MTO imprecision measurement, the absolute difference in period 2 is 50 and in period 4 is 40, therefore the total imprecision is 90. It is easy to see that this measurement inspires the customer to improve the forecast precision and to share them truthfully. It can be stated that the postponement of a part of the demand from period 2 to 4 results in double penalty, therefore this measure is proposed mainly in make-to-order production environments, where any change in the demand can necessitate costly rescheduling of production at the supplier.

On the other hand, the MTS imprecision measurement compares the total forecasted quantity with the total demand of the horizon. In this case, the decreased demand in period 2 is partially corrected with the increased demand in period 4, therefore the total imprecision becomes only 10. Accordingly, this approach is proposed in make-to-stock production environment, where demand is fulfilled from the inventory and thus postponing or urging the orders usually does not affect the production processes. In order to assure truthfulness, one can use a *rolling payment*: in this case, the customer pays for the imprecise forecast in period 2, but gets the compensation partially back in period 4. Even if the difference between the total forecast and the total demand was zero, if the forecast for a given period differs from the demand, this means an immediate compensation which will be returned only later. In order to avoid this, the customer is inspired to create and share as precise forecasts as possible.

Table 1. Imprecision measurement example

Period i	**1**	**2**	**3**	**4**	**Total**
Shared forecast $\hat{\theta}_i$	100	200	0	100	400
Realised demand ξ_i	100	150	0	140	390
Imprecision (estimated) d_{MTO}	0	50	50	90	90
Basis of compensation (MTO)	0	50	0	40	
Imprecision (estimated) d_{MTS}	0	50	50	10	10
Basis of compensation (MTS)	0	50	0	-40	

3.2 Extension: Considering Uncertain Product Life-Cyle

In the above basic VMI model, demand forecast of a component is provided by the customer for a multi-period, finite-length planning horizon. However, this demand is uncertain: it may stop whenever the demand for the end-product(s) built of the component ceases for any reason. In this situation called *run-out* the component inventory becomes *obsolete*. When the supplier applies make-to-stock production of custom components such a run-out is very problematic, since obsolete, unsolvable inventory may remain. The previously presented $t(\hat{\theta},\xi)$ payment can slightly compensate the supplier, since after the run-out the demand becomes zero, and therefore the customer pays for the imprecision. However, there are two problems with this approach: (i) the loss caused by the obsolete inventory is much worse than the harm caused by simple demand fluctuation, (ii) the information about the life-cycle uncertainty is completely disregarded. Therefore, the forecast should be extended with this new parameter: $\theta = (\theta_1, \ldots, \theta_n; p)$, where $p \in (0,1)$ is the estimated probability that run-out happens on the horizon. For such case, the following payment function can be applied:

$$t(\hat{\theta},\xi) = \begin{cases} c_0 \sum_{i=1}^{n} \xi_i + c_1 d_{MTS}(\hat{\theta},\xi) - c_2 \ln(1-\hat{p}) & \text{if no run-out happens on the horizon,} \\ c_0 \sum_{i=1}^{k-1} \xi_i + c_1 \left| \sum_{i=1}^{k-1} \left(\hat{\theta}_i - \xi_i \right) \right| - c_2 \ln(\hat{p}) & \text{if run-out happens in period } k, \end{cases} \quad (1)$$

where c_2 is a new parameter, the rate of the compensation for the life-cycle uncertainty. The structure of the payment is similar to the previous one, but in addition to the payment for the components and for the forecast imprecision, there is a new compensation term. Note that in spite of its minus sign, this latter term is positive, since the argument of the logarithm function is between 0 and 1. It can be proven that this payment is also strategy-proof even without applying rolling payment; for the proof we refer to Egri (2008).

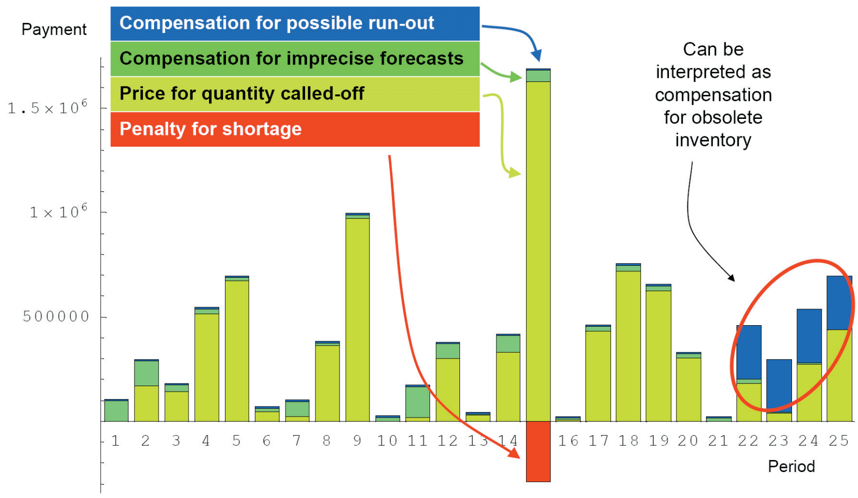

Fig. 2. Payment on a rolling horizon basis

Applying these payments on a rolling horizon means that in every period the compensation part of the payment depends on the imprecision of not only one forecast, but on the forecasts that were generated in the last n periods. In this case, in order to avoid multiple payments of the overlapping forecasts, $t(\hat{\theta},\xi)$ should be divided with the length of the horizon. Fig. 2 illustrates the parts of the payment function defined by Eq. (1), considering 4 periods long forecast horizons. For each period, the payment for the actual demand, the compensation for the forecast imprecision and the compensation for the life-cycle uncertainty are denoted. Note that the simulation software also computes an additional cost for production avoiding the shortage, but that term is independent from the payment. It can be observed that until no run-out happens, the third part of the compensation is not significant. In period 26 however, the demand ceases, therefore in the last four periods whose forecasts relate to period 26 the compensation is higher. This term automatically is increased due to the definition of Eq. (1), and it compensates the supplier for the obsolete inventory.

4 Application and Illustration

In parallel with the theoretical investigations of supply chain coordination, we also developed the Logistic Platform (LP), a software system for information sharing between a central assembly plant of an OEM and its suppliers (Váncza, *et al*., 2007). The system is in a daily use for two years. The LP is used among other tasks for sharing the medium-term consumption forecasts of around 10000 components weekly, in a rolling horizon manner. It calculates and presents the imprecision measurements described in the previous section, both in tabular and in graphical form, although they are not applied as a basis for compensation yet. Fig. 3 shows an example from the system, where the imprecision is indicated in a relative percental form, instead of the absolute values defined above. The plan deviation (PD) values correspond to the d_{MTS} metric without the absolut value, while the discounted absolute forecast error (DAFE) is the relative value of d_{MTO}. There are other three practically useful measurements indicated, which relate to the range and the direction of the forecast fluctuations.

Forecast week	Manufacturing week 2008-01-21 (-8)	2008-01-28 (-7)	2008-02-04 (-6)	2008-02-11 (-5)	2008-02-18 (-4)	2008-02-25 (-3)	2008-03-03 (-2)	2008-03-10 (-1)	PD
2008-01-14 (-9)	4,623.6	5,201.8	2,244.4	2,209.6					-10.7 %
2008-01-21 (-8)	3,218.4	5,688.5	9,835.7	3,359.1	2,719.2				19.7 %
2008-01-28 (-7)		5,597.6	4,756.9	9,386.7	3,028.2	3,432.0			24.8 %
2008-02-04 (-6)			3,657.3	6,163.8	6,643.5	3,460.8	2,370.3		-3.0 %
2008-02-11 (-5)				3,519.1	8,318.3	8,304.7	3,876.9	3,758.7	9.0 %
2008-02-18 (-4)					5,279.3	7,278.9	8,516.6	3,315.8	N/A
2008-02-25 (-3)						4,054.4	N/A	N/A	N/A
2008-03-03 (-2)							6,368.5	9,440.1	N/A
2008-03-10 (-1)								6,554.5	N/A
MND	0.0 %	-7.1 %	-38.6 %	-37.2 %	-48.5 %	-15.4 %	-62.8 %	-49.4 %	
MPD	43.7 %	1.6 %	168.9 %	166.7 %	57.6 %	104.8 %	33.7 %	44.0 %	
DFE	16.4 %	-1.5 %	52.5 %	71.2 %	14.2 %	55.4 %	-6.2 %	0.9 %	
DAFE	16.4 %	2.7 %	68.6 %	82.4 %	44.1 %	65.4 %	25.8 %	32.1 %	

Fig. 3. Forecast evaluation in the Logistics Platform

We analyzed the data stored in the application, and used them in a simulation system for determining the reasonable prices for the VMI service. The LP contains the forecasts and the realized demand, but neither the component prices nor the income and cost structure of the partners are available exactly. Therefore, we used realistic estimations for the component prices as well as for the supplier's setup and production costs. The numerical example below is based on 1000 simulation runs with the parameters of a specific component, on random generated rolling horizon forecasts of 25 periods, where each forecast is 4 periods long. According to the data from late 2007 and early 2008, the component had an average weekly demand of 113 units, with 88% fluctuation (d_{MTO}). This latter figure seems to be high, but it is ordinary for customized components. Recently, due to the global economic crisis, the uncertainty is even higher, and while the demand is decreasing, the fluctuation is 2-4 times higher. Since the demand planning modules of the enterprise systems cannot adapt quickly to the drastically changed market situation, the current forecasts overestimate the demand and they have to be corrected manually. For this reason, the behavior of the compensation scheme is illustrated with normal risks, and not under today's extreme circumstances.

Table 2. Summary of the simulation runs

Statistics	AVG	STD	MAX	MIN
Payment for components	282,825	31,910	382,800	175,000
Payment for deviations	102	18	180	56
Payment for possible run-out	20,203	0	20,203	20,203
Total payment	303,129	31,911	403,089	195,305
Supplier's cost	114,579	1,302	118,794	110,262

The results of Table 2 were computed with component unit price $c_0 = 100$, compensation rates $c_1 = 2$, and $c_2 = 40000$. Although c_1 is 2% of the price, the resulted average compensation payment (102) is only 0.036% of the payment for the components. However, the compensation for the possible run-out is relatively high, more than 7% of the payments for the components, which indicates that c_2 is probably too high. In addition to computing the payments, we also estimated the production costs, which helps characterizing the supplier's profit in the average, best and worst cases.

The presented compensation scheme has three parameters: the unit price of the components (c_0), the rate of the compensation (c_1) and the compensation for the possible run-out (c_2). Nowadays, only the first price is used almost uniquely, and every cost of the supplier (production, setup, logistics, uncertainty, etc.) is *hidden* in this parameter. This approach is easy for tuning the single parameter gradually, but harder to forecast its effects in a dynamically changing environment. Therefore, we propose separating the factors of the uncertainty, which results in a clearer, but more complex model. Setting multiple parameters appropriately is not an easy task any longer, and using simulations for supporting the parameter tuning seems to be necessary.

5 Conclusions

The channel coordination scheme presented in this paper is able to improve the overall efficiency of production and logistics processes and to compensate the supplier for the increased responsibility. However, it cannot guarantee fair profit sharing between the partners. Applying the mechanism design theory, we could prove analytically that in such a setting no VMI contract can guarantee a given profit sharing rate. Therefore, the idealistic goal of controlling profit allocation between the partners is unattainable.

Our proposed model of VMI service chooses the property of the individual rationality from the conflicting requirements and relaxes it. Similarly, relaxing other requirements leads to further models, which could be tailored to the specific industrial circumstances. While the budget balance seems to be necessary in practice in order to avoid the third party, the efficiency is often sacrificed by aiming only at quasi-efficiency. In fact, the strict assumption of the 100% service level can also be relaxed, which would lead to a completely different situation with backlogs or lost sales.

Finally, we intend to adapt our model to improve customize-to-order automotive supply chains, where long-term frame plans should be harmonized throughout the chains, while on the short term high flexibility is required. We are convinced that taking the mechanism design approach will also be fruitful in this setting, when elaborating practical business models for benefit balancing between cooperative partners.

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