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Designing cooperation mechanisms for supply chains

J. Váncza[a,b]*, P. Egri[a]

[a]*Fraunhofer Project Center on Production Management and Informatics, Computer and Automation Research Institute, Hungarian Academy of Sciences, H-1111 Budapest, Kende u. 13-17, Hungary*
[b]*Department of Manufacturing Science and Technology, Budapest University of Technology and Economics, H-1111 Budapest, Egry József u. 1, Hungary*

* Corresponding author. Tel.: +36-1-2796299; fax: +36-1-4667503. *E-mail address*: {vancza,egri}@sztaki.mta.hu

Abstract

The paper defines generic requirements towards cooperative planning in the nucleus of any supply network that is constituted by a pair of autonomous manufacturer and supplier who possess asymmetric information on demand forecast and costs, respectively. Then a novel way is suggested for investigating this problem by means of the apparatus of mechanism design. The analysis results in some provable generic properties as for efficiency and truthfulness, and shows the impossibility of fair cost and profit sharing. Further on, design principles towards a payment scheme are devised that provide incentive for the partners to cooperate in order to minimize costs. This payment can be considered the price for a flexible supply service. As examples, the generic framework is instantiated with two particular cooperative supply mechanisms.

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Keywords: Supply chain management; cooperation; mechanism design.

1. Introduction

The paper exposes the problem of *cooperative planning* in supply chains where partners have asymmetric knowledge of demand and supply related information, and decide autonomously, by considering their own, eventually conflicting objectives. The supply chain is supposed to operate in an environment that generates *uncertain demand*. The key questions are how to achieve acceptable emergent behavior of the partners with guaranteed properties that relate to the global performance of the overall system, like service level, total cost, stability, or energy and/or eco-efficiency. Such or similar questions are in the core of sustainable manufacturing that can be attained only if individual, profit maximizing partners are willing to cooperate [12]. The paper suggests a novel methodology for modeling and analyzing this problem, as well as devises generic design principles for cooperative supply planning.

In particular, we investigate the problem of coordinating the medium-term planning level decisions of autonomous partners in a two-echelon supply chain where the *manufacturer* of end-products is in the role of the buyer who needs component delivery from the *supplier*. The manufacturer, being closer to the market of end-products, prepares forecast for market demand, plans its production and generates the dependent demand for components. This forecast is its own, local information. On the other hand, the supplier has its private information about production costs that are essential for making appropriate decisions about the production of components. Supply can be considered a *service* that is burdened by (1) uncertainty of the market demand, as well as (2) the strategic manipulation of information possessed by the partners. E.g., given the risk of component shortage, the manufacturer may tend to forward inflated forecasts to the supplier. Alternatively, if planners at the manufacturer's side are rewarded for over-performing their plans, then they deliberately underestimate the demand and share too pessimistic forecasts with the suppliers [4]. The supplier, however, will try to outwit its partner and tinker with the forecast. All this typically leads to corrupted service,

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frequent contingency planning, obsolete inventories and additional costs.

The supply chain management (SCM) literature is typically rich in process design, while widely neglects the necessary governance structure [3][8]. It is also well-known that there are serious differences between theory and practice of SCM, mainly due to the absence of strategic elements in the collaboration [10][12]. In this paper we try to bridge this gap by elaborating the key requirements of cooperative planning and handling its strategic implications by taking the approach of *mechanism design* (MD).

Mechanism design, also considered inverse game theory, has a specific engineering perspective. It applies the model of non-cooperative games with agents having incomplete information, and investigates how the private information influencing the other agents' utilities can be elicited [2][9]. Accordingly, MD can resolve dilemmas and suboptimal performance in strategic situations by aligning the objectives of the partners. Since this theory considers strategic interactions of self-interested agents with asymmetric (private) information, it offers promising applicability also in supply chain research [1][12]. In the sequel we design a cooperative supply protocol that controls the flow of material, information and financial assets. The model helps answering questions whether and how partners are interested in telling unbiased information, can make decisions that are globally efficient, or share their costs in a fair way.

2. Problem statement

The generic requirements towards a mechanism that facilitates cooperative planning specify, on the one hand, the frame of a theoretical model. On the other hand, however, they concur with the conditions and expectations of managerial practice. Summing up, we seek mechanisms that meet the following criteria:

- *Autonomy*: Local information, utilities and decision rights of the partners have to be respected. Since each partner has to exercise control over future events in its own premises, planning problems must be solved locally.
- *Strict asymmetry*: Any knowledge or belief about the other party's private information and internal planning process is excluded.
- *No third party*: The mechanism should not involve any new party in the decisions making (e.g., broker, facilitator, etc.). Every decision should be made by the partners who form the chain. Note that this – together with autonomy – implies a decentralized implementation.
- *Strong solution concept*: The mechanism has to guarantee that the decisions of the partners are dominant, i.e., could not decide better given the decision of the other party.
- *Efficiency*: The mechanism should achieve the optimal network-wide solution which is, in our case, the minimal expected total cost.
- *Participation*: In order to assure participation of the partners, the mechanism should guarantee non-negative profit for each partner.

There are further requirements towards planning and execution that are essential in real-world applications:

- *Uncertainty*: Any cooperative planning method should be able to handle uncertain demand forecast and even confidence in demand forecast.
- *Responsiveness*: Planning has to be provided feedback from realization, and the mechanism should have an element for correcting eventual fallacy of planning (like rolling horizon planning, or, in case of inventory glitches, a new production cycle, backordering, compensation for lost sales or obsolete stocks etc.) [12]. Feedback from realization is, however, common knowledge of the parties.
- *Tractability*: The forecasting and planning algorithms should be computationally tractable.

As a *solution*, we seek a decision making and communication protocol that locates each necessary decision to be made and arranges the flow of information, material and financial assets between the market and the supply chain, as well as between the parties who constitute the chain.

3. The mechanism design approach

3.1. The basic model

This section presents a basic model of the cooperative supply service with the application of the concepts of mechanism design. The model is a variant presented in [6]. For the sake of the theoretical analysis we temporarily disregard some of the initial requirements and insert a *mechanism* in between the manufacturer and the supplier. This *central authority* will receive information from both parties, make the planning decision and arrange the flow of payments between the parties according to the following protocol (see Fig. 1):

1. Forecasting demand (manufacturer).
2. Sharing private information, i.e., forecasts (manufacture) and costs (supplier) with the mechanism.
3. Planning and ordering (mechanism).
4. Producing (supplier).
5. Consuming according to realized demand (manufacturer).
6. Paying (all, including the market).

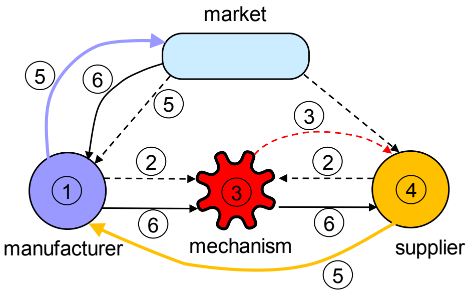

Fig. 1. The classical mechanism design protocol

The crux of the problem is that we have to prevent the *strategic manipulation* of information the partners possess privately, i.e., the forecast and cost. As it was shown earlier, in a typical business scenario both parties may have a number of incentives to distort this information. However, without the truthful disclosure of such information optimal planning is not possible. So as to prevent manipulation, *taxes* will be introduced that affect the individual utilities of the partners. Taxes are realized as transfer payments between the parties and the central mechanism [2]. Further analysis hence requires a distinction of real and communicated information, as well as the clarification of payments and utilities.

3.2. The formal model

Elements of the formal that are needed to capture the basic mechanism supposing a central authority are shown in Fig. 2. The symbols and their definitions are also summarized in Table 1 below.

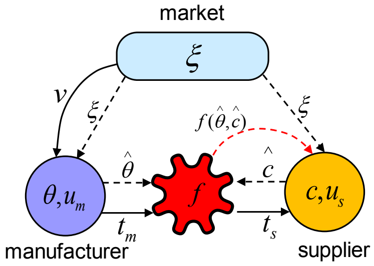

Fig. 2. The formal model of the coordination mechanism

As for the *information* available for the partners, we take the following assumptions:

- Each partner has some *private information*: the manufacturer knows the θ demand forecasts, while the supplier knows the *production cost* structure, denoted by c. However, no a priori belief about the other's information is maintained. For instance, no assumption is made on the form of forecasts.
- The disclosure of private information is not necessarily truthful. Hence, the manufacturer may communicate $\hat{\theta}$ instead of θ, and the supplier $\hat{c}$, instead of its known cost c.
- Realization of demand ξ in the market is, however, commonly known by each partner, including the central mechanism.

As for *decision making* and its consequences, the following basic assumptions are taken:

- Decisions are aimed at completely fulfilling *uncertain demand*.
- Planning decision is made by the central authority using a *choice* (or planning) function *f* that calculates an optimal production plan x in response to a given demand forecast and cost parameter.
- If demand is overestimated, obsolete inventory stacks ups. If demand is underestimated, new production setup is required and backlogs are generated. In any case, extra costs are incurred.
- Real costs denoted by $c(x,\xi)$ are the consequences of planning decisions and realized demand. The total of production and inventory costs are accumulated on the side of the supplier who provides the service.
- Both partners are rational and maximize their own *utility*. Utility of the manufacturer (u_m) can be expressed as the difference of its income from the market (v) and its *payment* (t_m) to the central mechanism. In turn, utility of the supplier (u_s) is the payment received from the central mechanism (t_s) minus its incurred real production costs (c).

Table 1. Basic notions and symbols of the formal model

Demand and production related information	
real and communicated demand forecast	$\theta,\hat{\theta}$
real and communicated production cost	$c,\hat{c}$
choice (planning) function	$f(\hat{\theta},\hat{c})$
production plan determined by the choice function	X
realized demand at manufacturer	ξ
realized cost at the supplier	$c(x,\xi)$
Payments and utilities	
payment function of manufacturer	$t_m(\hat{\theta},\hat{c},\xi)$
payment function of supplier	$t_s(\hat{\theta},\hat{c},\xi)$
income of manufacturer	$v(\xi)$
utility of manufacturer	$u_m=v(\xi)-t_m(\hat{\theta},\hat{c},\xi)$
utility of supplier	$u_s=t_s(\hat{\theta},\hat{c},\xi)-c(f(\hat{\theta},\hat{c}),\xi)$

3.3. Fundamental properties of the mechanism

When the performance of the overall system is an outcome that emerges from the interaction of local decisions, it is essential to state some analytic, provable properties of the supply chain's operation. In the sequel we define the basic properties of the generic supply coordination mechanism. From the definitions some theorems can be derived. (The proofs are omitted for lack of space, for details see [6][7]).

Note that the mechanism is determined by its choice function and the payments it arranges. *Strategy-proofness* reflects the issue whether and how truthfulness pays off. A mechanism $M=(f,t_m,t_s)$ is strategy-proof, if truth telling is a dominant strategy for every partner, i.e., it maximizes their expected individual utility. (M is strongly strategy-proof if telling the truth is the only strategy that maximizes expected utility.) Formally, strategy-proofness can be expressed for the case of the manufacturer and supplier as follows:

$$\forall \hat{\theta},\hat{c}: \mathbf{E}_\theta\left[u_m(\theta,\hat{c},\xi)\right] \geq \mathbf{E}_\theta\left[u_m(\hat{\theta},\hat{c},\xi)\right] \tag{1}$$

$$\forall c,\hat{c},\hat{\theta}: \mathbf{E}_{\hat{\theta}}\left[u_s(c,\hat{\theta},c,\xi)\right] \geq \mathbf{E}_{\hat{\theta}}\left[u_s(c,\hat{\theta},\hat{c},\xi)\right] \tag{2}$$

Efficiency relates to the consequences of decisions and the performance of the overall system as seen from an external point of view. In our setting, these “material” decisions on production quantities are made solely by the $f(\theta,c)$ choice (or planning) function. Hence, the mechanism is efficient, if f maximizes social welfare, i.e., the sum of the expected utilities of the partners without the internal payments. This is just the total income of the system from the market minus the actual production costs. Formally,

$$\forall \theta,c: f(\theta,c) \in \arg\max_x \mathbf{E}_\theta\left[v(\xi)-c(x,\xi)\right] = \arg\min_x \mathbf{E}_\theta\left[c(x,\xi)\right] \tag{3}$$

Shortly, the mechanism is efficient if it minimizes the expected total cost in face of meeting uncertain demand.

If a mechanism is *both* strategy-proof and efficient, then its optimal overall performance is *guaranteed*. However, this nice property comes hand in hand with another one: the *impossibility of “fair” cost sharing*. We have proven that if $M=(f,t_m,t_s)$ is a strategy-proof and efficient mechanism, then the payment to the supplier does not depend on its cost [6]. Formally,

$$\forall c,\hat{c},\theta,: \mathbf{E}_\theta\left[t_s(\theta,c,\xi)\right] = \mathbf{E}_\theta\left[t_s(\theta,\hat{c},\xi)\right] \tag{4}$$

$t_s(\hat{\theta},\hat{c},\xi)$ reduces to $t_s(\hat{\theta},\xi)$. (5)

Hence, the supplier may claim whatever cost, but the payment t_s received for its contribution will depend on the communicated and realized demand quantities only. No one cares how this demand was satisfied on the side of the supplier. This implies that the supplier can maximize its utility solely by minimizing its costs.

Finally, the last fundamental property is *budget balance*. The mechanism $M=(f,t_m,t_s)$ is budget balanced if there is neither surplus nor deficit in the payments. Hence, no payments or debts are accumulated in the mechanism. Formally expressed,

$$\forall \hat{\theta},\xi: t_s(\hat{\theta},\xi) = t_m(\hat{\theta},\xi) \tag{6}$$

Note that budget balance is a necessary requirement of removing the third party from the classical centralized design shown in Fig. 1 and Fig. 2 and setting up a decentralized supply chain coordination scheme that fits our original requirements.

3.4. Designing a decentralized coordination mechanism

The above conceptual framework helps capturing the key elements and general characteristics of the coordination mechanism that should comply with the requirements listed in Section 2. Clearly, we need a strategy-proof and efficient mechanism that warrants also budget balance.

One of the essential general results of MD is that given any efficient choice function f, it is possible to construct a payment scheme that guarantees strategy-proofness. In such so-called *Grooves mechanisms* the payment received by each partner from the mechanism has the form $t_i(.)=g_i(.)+h_i(.)$, where $g_i(.)$ is the total social welfare of all partners except i in case of an optimal choice, while $h_i(.)$ is an arbitrary function whose outcome does not depend on the information communicated by i. The intuition behind this scheme is that nobody is interested in strategically manipulating the communicated information, while, at the same time, has a definite interest in increasing all the others’ income. Anyone who acts according to this incentive and assumes that all the other rational partners behave in a similar way, can reasonable expect that its own utility will also be maximized in case of an optimal decision. Hence, the payment scheme provides an incentive for telling the truth, and, after all, for cooperation. As for budget balance, it is a well-known result that the Grooves mechanism excludes this property; i.e., in the general case there is no mechanism that is efficient, strategy-proof and budget-balanced at the same time [11].

After removing the central agency we get a *decentralized supply chain coordination model*, where both the protocol and the forms of information and financial flows are well-specified (see Fig. 3). Planning is performed by the supplier, hence there is no need to communicate costs. Both the manufacturer’s demand forecast and payment are directed immediately to the supplier. However, even though it has no active role any more, the mechanism is still there in the shadow and specifies the payment if we are going to warrant useful properties like efficiency and strategy-proofness.

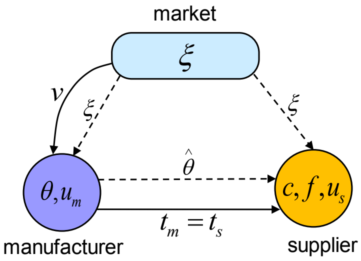

Fig. 3. The decentralized supply chain coordination model

The only open question is that of the payment. Payment formula of the Grooves mechanism cannot be applied because of eq. (6). Though, a specific feature of the problem is that the communicated forecast can be *verified* at the time when demand ξ is realized. A strategy-proof payment can be constructed in following form:

$$t_m(\hat{\theta},\xi) = g(\hat{\theta},\xi) + h(\xi) \qquad (7)$$

where h is an arbitrary function while g warrants that whenever an event ξ is drawn from a distribution θ, then

$$\mathbf{E}\left[g(\theta,\xi)\right] < \mathbf{E}\left[g(\hat{\theta},\xi)\right]. \qquad (8)$$

This means that truthful forecast sharing is a rational decision of the manufacturer.

4. Supply chain coordination mechanisms

So as to get a supply mechanism applicable in a practical setting, the above framework has to be filled in with detailed specification of how to (1) make forecasts, (2) do planning, and (3) arrange payments. In the sequel we present two kinds of such expansions.

4.1. Single-period supply with expected forecast

In the simplest case, assume a single period model where the manufacturer generates forecast as *expected value* of the market demand. (Note that most supply planning systems cannot handle stochastic problems.) In case of shortage corrective planning scheme is applied (emergency production, backordering, etc.) In this case it is easy to see that the payment function in the form

$$t_m(\hat{\theta},\xi) = \alpha\left|\hat{\theta} - \xi\right| + \beta(\xi) \qquad (9)$$

where $\alpha > 0$ is a constant, and β is an arbitrary function, provides a mechanism that is strongly strategy-proof. The second term covers payment for the delivered products, while the first term defines the price of *flexibly supply service*. The closer the forecast is to realized demand, the cheaper is the service. Hence, the manufacturer has an incentive to generate as good a forecast as possible.

4.2. Newsvendor supply with emergency production

Now we expand the above model by assuming that forecast is given by the *expected value* and *standard deviation* of the demand (m and σ, respectively). However, no specific demand distribution is assumed. In this case, the manufacturer communicates the pair $(\hat{m},\hat{\sigma})$ to the supplier. The supplier plans and produces accordingly, but if actual demand exceeds produced quantities, makes an *emergency setup* so as to cover the shortage. This emergency production incurs, of course, extra costs. Note that this model is an extended version of the so-called *newsvendor* model where optimal lot sizes can be calculated (for details, see [7]). Once having a choice function that is able to generate an optimal plan on the side of the supplier, the crux of the remaining problem is to construct a strategy-proof payment function for the manufacturer. While upon execution the difference of expected and realized demand can easily be measured, the accuracy of the standard deviation can hardly be assessed based on a single observation. Though, there is a way out of this dilemma, if we fill in the generic payment formula in eq. (7) appropriately. Specifically, we have proven that the payment function in the form

$$t_m(\hat{m},\hat{\sigma},\xi) = \alpha\left(\frac{(\hat{m}-\xi)^2}{\hat{\sigma}} + \hat{\sigma}\right) + \beta(\xi) \qquad (10)$$

where $\alpha > 0$ is a constant, and β is an arbitrary function, is strongly strategy-proof [7]. That means that the manufacturer can maximize its utility if its communicated $\hat{m}$ and $\hat{\sigma}$ values are as close to the ideal distribution of demand as possible. The interpretation of this composite payment is as follows: (1) the last term is the price of the delivered products. The first term is again the price for flexible service that has now a factor (2) that is proportional with the *imprecision* of forecast, and (3) a second factor that is proportional with the *uncertainty* of communicated demand forecast. Summing up, the payment expresses the cost of *flexible supply service* that meets all the requirements presented in Section 2.

4.3. Computational example of the newsvendor supply

Even though the above mechanism has some guaranteed properties, one has to make extensive computational test so as to set parameters of the payment function appropriately and to investigate the possibilities of a reasonable cost or profit sharing. Now we demonstrate on a single example how the payment in eq. (10) compensates the supplier for the increased uncertainty of the demand. We assume a linear payment for the products, i.e., $\beta(\xi)=p\xi$ where p is a fixed unit price. With the parameter values p = 10, α=2, m=1000, Fig. 4 shows how the payment increases when the standard deviation σ varies in the range [1,400] assuming normal distribution of the demand. Average payments have been calculated on 1000 random demand data for each σ.

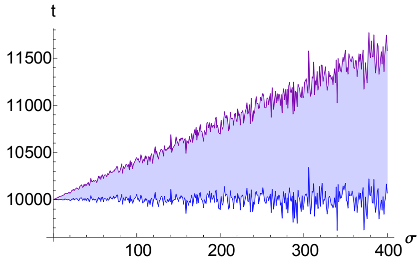

Fig. 4 Payment to the supplier with increased forecast uncertainty

As Fig. 4 shows, the payment for the products oscillates around the expected value of demand (pm = 10000), while the payment for the supply service increases with the standard deviation, which means that the supplier gets higher compensation on a riskier market. The gradient of the curve, i.e., the ration of risk sharing, can be controlled with the parameter α.

The *participation* of partners can be warranted if the service is profitable for both of them. However, they have to come to an agreement on the choice of the parameter α and the function β *before* the service. And this is the point where theory ends (remind the impossibility of fair cost sharing) and a new avenue is to be opened for the systematic simulation and negotiation over factors of the payment.

5. Conclusions

In the paper we defined the generic requirements towards cooperative planning in the nucleus of any supply network that is constituted by a pair of autonomous manufacturer and supplier. Supply was considered a service in face of uncertain demand forecasted by the manufacturer. We suggested a novel way for handling this problem by means of the conceptual and methodological apparatus of mechanism design. This approach led to generic design principles towards a coordination protocol (including payment schemes) that warrants truthfulness and global efficiency. The analysis resulted also in some negative results: even though the requirements as for cooperative planning are one by one reasonable, unfortunately, their set as a whole implies contradiction. Hence, some of the claims have to be relaxed. The design principles of the mechanism cast an empty framework that have to be filled in with particular choice functions and payments that fit the conditions of an actual supply planning problem. In a nutshell, such details of two particular mechanisms were also presented. We can but note here that the cooperative planning mechanism we developed earlier for a multi-period, stochastic and rolling horizon supply planning problem can also be re-casted in the generic framework presented here [4]. Beyond ensuring participation – which is an open problem – the requirement of *tractability* raises also a severe issue when it comes to planning [1][9]. The algorithmic problem should be solved on a case by case, depending on the actual planning model applied. Finally, the methodology can be applied in settings that involve multiple partners [6], or flexible supply service including lost sales.

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