RESEARCH PAPERS OF THE WROCŁAW UNIVERSITY OF ECONOMICS
No. 35 — 2008
Advanced Information Technologies for Management – AITM 2008

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RISK MANAGEMENT AND INFORMATION DISCLOSURE IN SUPPLY CHAIN ANALYSIS

Abstract: Supply Chain Management (SCM) has become an important issue in business modelling, with the aim of reducing the manufacturing cycle time, delivery lead-time, and inventory stocks. Traditional SCM technologies view supply chain risk as an explicit variable that can be accounted for, quantified, and optimized. However, managing risks related to the behaviour of supply chain participants requires some additional formalization to quantify the total risk associated to a particular configuration of the supply chain. Individual coalition participants can evaluate, computing a fairness function, to which extent the common good objective of the supply chain will keep them away from their individual objectives. In this paper we argue that if this distance is too great, individuals will adopt uncooperative behaviour to push the coalition back to a situation fairer to them, moving away from the common good. We propose a game-theoretical approach to evaluate a coalition's lack of balance and derive a risk assessment methodology out of it.

1. Introduction

In today's highly competitive market, manufacturers face the challenge of reducing the manufacturing cycle time, delivery lead-time, and inventory. However, every organization has its own objectives and its own decision-making processes. This lack of integration has historically triggered conflicts and prompted the need for a mechanism to resolve them, achieving seamless process integration.

A Supply Chain (SC) is a network of suppliers, factories, warehouses, distribution centres and retailers, through which materials are acquired, transformed, produced, and delivered to customers. Born in the early 1990s, Supply Chain Management (SCM) has become an important issue in business modelling. Also, a large number of software packages have emerged, called SCM or Advanced Planning and Scheduling (APS) systems. SCM systems apply advanced coordination and planning techniques to create plans that take into account most of the factors and constraints that limit the ability to deliver on time and with minimal costs.

Collaborative supply chain management largely consists of the combined optimization of supply and delivery within the virtual organization defined by the supply chain boundaries. Actors participating to a supply chain have a clear shared interest for achieving a *common good*, in term of revenue or profits. Optimization is carried out to sustain competition with other supply chains working in the same business area. While global (i.e., supply chain-wide) optimization can reduce the chain's overall cost and preserve its competitiveness, local decision making about supplies and delivery does not lead to globally optimal solutions. Existing supply chain models provide all the notions needed to support basic algorithms which tune the supply chain to deliver its goods on time and with minimal cost.

However, it must be considered that each actor participates to the coalition with its own objectives which need to be re-conciliated with the achievement of the common good. We can assume that individual actors will be willing to co-operate toward global optimization, seen as the coalition's common good; but if achieving such common good requires completely missing their objectives, actors may be tempted to adopt a non-cooperative behaviour.

Considering this perspective, it is clear that one of the aims to be achieved by SCM is risk reduction. Traditional SCM technologies view supply chain risk as an explicit variable that can be accounted for, quantified, and optimized. For instance, the primary goal of production planning is to optimize resource allocation and production scheduling, reducing the risk of failure to deliver or the risk of factory underutilization or shutdown. Although it looks clear that SCM must explicitly manage the opportunity and threats that the supply chain itself presents, the study of risks introduced by SCM itself is a less explored topic. Qualitative analysis has been attempted of some risks related to the supply chain structure, such as the ones posed by sourcing in isolation to logistics or distribution networks [Jüttner 2005]. Such qualitative analysis has been often carried out by means of surveys. However, managing risks related to the behaviour of supply chain participants requires some additional formalization to quantify the total risk associated to a particular configuration of the supply chain.

This conflict of interest and the resulting risk can be described as an information sharing problem. Supply chain optimization is based on data provided by each partner in the supply chain. In other words, each actor needs to share information with other partners or with a trusted external decision maker. In this cooperative scenario, there seems to be little need for privacy or access control techniques; indeed, many inter-organizational knowledge management systems have been set up with the idea that the more information is shared, the better it is for the coalition [Lee Hau, Wang 2000]. But the data to be shared may include information usually kept confidential within the company, like per-item production and transport costs, prices, stock levels, and other inventory. Their release or sharing can induce an assessment on the part of each actor of its own profitability, and if achieving the common good requires completely missing their objectives, actors may be tempted to adopt non-cooperative behaviours to push the coalition back to a situation fairer to them, moving away from the common good [von Lanzenauer, Pilz-Glombik 2002; Clark, Scarf 1960]. In other words, in a cooperative scenario where information is shared without any privacy protection any actor can evaluate how much achieving the common good will keep them away from achieving their individual objectives [Ceravolo et al. 2008].

The general claim of this paper is that the problem can be faced computing the distance between the common good in terms of cost reduction and the maximum fairness in terms of *distributive justice* of the chain. This is achieved applying a game-theoretical model where the supply chain actors are the player of a game, and the game goal is to maximize revenues.

2. Traditional risk management and information disclosure

Traditionally, the notion of *Supply Chain Risk* has been used to designate various types of unfavourable events (see [Gaonkar, Viswanadham 2004] for a classification) affecting one or more of the supply chain actors, jeopardizing the achievement of the supply chain's business goals. Early efforts toward supply chain modelling did not explicitly address risk; however, being able to assess a supply chain vulnerability to sudden disruptions is today a major modelling requirement. It is widely recognized [Jüttner et al. 2003] that supply chain models need to be enhanced to include means by which risks can be represented and addressed, increasing the supply chain's *resilience*. Experience has shown that security-related events such as intrusions and viruses are only some of the possible causes of supply chain disruptions; indeed, a major source of supply chain risk is unexpected behaviour on the part of supply chain participants.

Risks related to the behaviour of supply chain participants include the ones linked to sudden changes in supply, market and warehouse capacity. If a major product line is fuelled by a sole supplier, its operation may be at risk if the supplier capacity becomes suddenly lower. When a supply chain has multiple suppliers, supply issues may arise when high percentages of a crucial product (in dollars or unit volume) are sourced from few top suppliers. Similarly, when a supply chain has multiple Points of Sale (POS), market issue may arise when market demand at one or more POS changes, e.g. as an effect of a variation in shelf space. Finally, a similar remark can be made for warehouse capacity, which can oscillate due to seasonal trends, and is anyway dependent on the goodwill of a limited number of supply chain actors.

Identification of behaviour-related risk is just the first step of supply chain risk management. Once the supply chain's potential risks have been identified, a *risk* *owner* should be assigned to each. It will be the owner's responsibility to report periodically on the risk handling strategy on a periodic basis. For each risk, the owner must assess what the financial impact will be to the organization in the event of a disruption. The actual risk values are computed by (i) assigning a probability to the risk, (ii) multiplying the financial impact by the risk probability. Finally, risks are prioritized in order to get more management attention, i.e. the supply chain risk analysis results are ordered by descending dollars. Conceptually, our work is aimed at paving the way to develop techniques for assigning a probability to the risks related to potential non-cooperative behaviour of supply chain participants. Such probability can be estimated for each actor based on how much the current operational situation of the chain is perceived as fair by the actor himself. If the situation is perceived as grossly unfair, the actor is likely to adopt non-cooperative behaviour, e.g. introducing (or simulating) sudden variations in supply, market or warehouse capacity.

3. Supply chain fairness and the Shapley Value

A research approach considers supply chain actors (i.e., suppliers and resellers) as the players of a game, characterized by strategic interdependence (the payoff for what a player chooses to do will depend also on what the other players do, and this holds for all players) [Cachon, Netessine 2003]. Each player is considered unboundedly rational and pursues the maximization of her own payoff corresponding to her revenues. The game equilibrium, called Nash Equilibrium, is attained when each player plays her best response strategy to all other players' best response strategies: this configuration is such that no player would obtain a higher payoff by deviating unilaterally from it.

Here we are interested in the case where participants in a supply chain can collude, because the actors will keep their selfish attitudes: whatever pair of prices they will choose, there will always be another pair of prices which would be better for one of the two, and worse for the other. In other words, a problem on how mutual profits could be redistributed within the coalition will eventually rise anyway.

There are several kinds of solutions to the problem of distributive justice. Due to the subjectivity of satisfaction criteria for each agent an objectively optimal solution cannot in general be attained, however a solution fulfilling some largely accepted requirement can be obtained by following the prescription dictated by the so called Shapley Value (SV). The SV consists in a unique allocation of the surplus for each coalition.

In a general game with a set N of n players any subset of players in N is a potential coalition C. A coalition can strike deals among its own members to exploit all the available mutual advantage. There are $(2n - 1)$ possible coalitions, altogether, including the grand coalition, consisting in N itself. The *security level* of a coalition C is a quantity $v(C)$ expressing the total surplus that its members can achieve on their own even if the non-members took the action that was the worst from C's perspective.

An allocation is a list of surplus amounts for the players, an allocation is blocked (i.e. not even considered) by a coalition C if the allocation values add up to an amount which is less then security level. The set of allocations that cannot be blocked by any coalition is called *core*: it contains all the possible reasonable deals.

The core can be a point, a range or a general set. For some games, it can even be empty. However, the core has some desirable properties: since it cannot be reduced further by any groups searching for a better deal, including the grand coalition, it can be easily shown [DS04] that is Pareto efficient, i.e. that no other allocation will improve everyone's payoff simultaneously. Note that even the core, being defined on the base of an inequality over a sum of the allocation array, does not give any guarantee over the distributive justice of an allocation: the elements of the core will all represent efficient allocations, but some will be fairer than others. The Shapley Value is an allocation of payoffs u_i, where i is the index pointing to the i-th game participant, defined as follows:

$$u_i = \sum_C \frac{1}{n\binom{(n-1)}{(k-1)}} \left[v(C) - v(C-i) \right]$$

where the sum is taken over all the coalitions that have i as a member, and where $k = k(C)$ is the size of the coalition. The idea is that each player should be given a payoff equal to the average of the contribution that he makes to each coalition to which he could belong (all coalitions are regarded as equally likely in some sense and all agents are equally likely to participate into a coalition).

The expression in square brackets represents the difference between the security level of the coalition C and the one that the remaining agents would have if the agent i were removed: this measures the contribution of i to C.

The Shapley Value guarantees that a coalition can neither be attacked by defection of sub-coalitions, nor be blocked by the grand coalition. A distribution following the Shapley Value must be Pareto efficient. Notice that the set of Pareto efficient allocations contains both the core (which can be empty, or a point or a set) and the Shapley Value (which is always a point). However in general the Shapley Value needs not to be within the core.

4. Supply chain modelling and analysis

We are now ready to model a simple supply chain by giving an annotated value model of the exchanged objects and sketch its analysis by computing the associated Shapley Value for an example situation. By studying the possible allocation of the profit inside the chain, it will be possible to compare the status of the chain w.r.t. the *fairness point*, i.e., the point where the revenues are allocated to each participant according to its contribution, and the *optimal point*, i.e., the point which minimizes the overall costs of the chain or maximizes the overall revenues. The distance of the current status of the chain (say, the one achieving the chain's common good by optimizing the objective function) from the fairness point provides each actor with an estimate of the convenience, for that actor, to well behave in the supply chain. Should the convenience become too low, the actor will be tempted to behave uncooperatively according to some uncooperative behaviour model. Such behaviour may bring a damage to the overall supply chain operation (e.g., pushing it away from the optimal point) which could be avoided by obfuscating the information needed to compute fairness (while continuing to perform the chain optimization).

We shall consider a Manufacturer M and two Resellers, R_1 and R_2 who satisfy the market request MR. Resellers buy a given quantity q_i of products from M and sell a quantity of products s_i less than or equal to the market capacity θ_i.

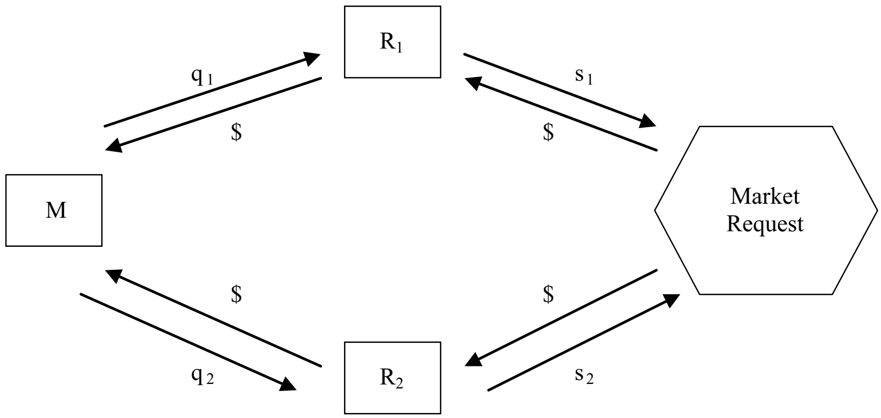

Figure 1. Value model for the sample supply chain

The total revenue of the chain can be computed as $p_1q_1+p_2q_2+r_1s_1+r_2s_2$. Let us make two simple assumptions, one regarding the profit of each reseller which is obtained by raising of a quantity δ_i the buying price, i.e. $r_i=p_i+\delta_i$. The second assumption is about the quantity of products sold by the resellers which is equal to the quantity bought, i.e. $q_i=s_i$ (we are assuming no stocks). In this situation, the chain can be modelled as the following optimization problem:

$$
\begin{aligned}
\max R &= p_1q_1+p_2q_2+r_1s_1+r_2s_2,\\
m &= s_1+s_2,\\
s_1 &< \theta_1,\\
s_2 &< \theta_2,
\end{aligned}
$$

where m is the overall quantity absorbed by the market. To simplify the analysis, let's also assume that the prices are equal, $p_i = 1$ and the profits are constant and equal to 0, i.e. $\delta_i=0$, and the market capacity are $\theta_1=70$ and $\theta_2=60$, respectively. The total revenue of the chain can now be expresses as $2p_1q_1+2p_2q_2$. Fixing the revenue for example to \$200, it is possible to apply the Shapley analysis and obtain the results shown in the following Table 1.

Table 1. Shapley Value computation for the sample supply chain

Contribution to the coalition			
Permutation	M	R_1	R_2
M, R_1, R_2	0	140	60
M, R_2, R_1	0	80	120
R_1, M, R_2	140	0	60
R_1, R_2, M	200	0	0
R_2, R_1, M	200	0	0
$R_2\, M, R_1$	120	80	0
Σ	660	300	240
Shapley Value	0.55	0.25	0.20

Intuition suggests that each actor alone cannot generate any value, i.e. $v(M)=v(R_1)=v(R_2)=0$. Also, it is easy to see that $v(M, R_1)=140$, $v(M, R_2)=120$ and $v(R_1, R_2)=0$. Table 1 shows the details of the computation of the Shapley value for each permutation. The first row is computed as follows: the manufacturer M cannot generate any revenue on its own. Adding the reseller R_1 to the coalition, makes the total revenue rise to 140, meaning that R_1 contribution to the chain's revenue is 140. If the coalition is completed by R_2, the generated revenue will be 200; so the contribution of R_2 is 60 in this case. In the second row, the second reseller R_2 is added to the coalition before R_1, contributing for 120 to the chain revenue. Then reseller R_2 contributes for 80 to the overall revenue. The same line of reasoning explains the other rows of Table 1. Adding up the figures in each column gives the total contribution of each actor to the chain revenue. If there is a total bonus, a "fair" partition of the bonus is the one giving to each reseller a fraction of the bonus proportional to the Shapley contribution to the revenue, as shown in the last row. However, the actual partition used in practice will rather be the one minimizing the chain cost function; an intuitive partition for instance, could be 50% for M and 25% for each reseller. Comparing such partition to the one computed in Table 1, gives a fair sharing to R_1 only. R_2 is more likely to adopt uncooperative behaviour in order to push the chain back toward perceived fairness, even at the expense of the overall competitiveness, i.e. against the common good.

Let us now consider a modified scenario, where the profit is computed proportionally to the product quantity by a factor α_i. Now the total revenue of the supply chain can be expressed as:

$$(1+\alpha_1)p_1q_1+(1+\alpha_2)\, p_2q_2.$$

Fixing $\alpha_1 = 1$, $\alpha_2 = 2$, considering unitary prices, i.e. $p_i = 1$, one gets $2q_1 + 3q_2$ and the overall supply chain can be modelled as:

$$\begin{gathered}\max R = 2q_1 + 3q_2,\\ 100 = s_1 + s_2,\\ s_1 < 70,\\ s_2 < 60.\end{gathered}$$

The optimal point for the chain, will be the one filling up all the R_2 capacity first (maximizing then the total revenue). Fixing $s_2 = 60$, then 40 is assigned to s_1 obtaining a total revenue of 360 for the chain, which can be split among the participants, giving 100 to *M*, 80 to R_1 and 180 to R_2. It is possible to note that the optimal point does not correspond to each actor generation potential averaged over all the supply chain configurations. Indeed the Shapley analysis returns the following Table 2.

Table 2. Shapley Value computation for the modified supply chain

Contribution to the coalition			
Permutation	M	R_1	R_2
M, R_1, R_2	0	210	120
M, R_2, R_1	0	120	240
R_1, M, R_2	210	0	120
R_1, R_2, M	360	0	0
R_2, R_1, M	360	0	0
R_2, M, R_1	240	120	0
Σ	1170	450	480
Shapley Value	0.55	0.22	0.23

Here *M* is generating her revenue at the optimal point rather than at the fairness point. He is a critical actor. If she gets to know that there is a difference between α_1 and α_2, he will raise the price p_1, increasing then the revenue she herself generates as well the total revenue of the chain. For instance with $p_1 = 2$, the optimal point becomes $s_2 = 70$ and $s_1 = 30$, with a total revenue of 370. This is better than the previous point, but note that it could be not sustainable for the supply chain, for example because the price is high and not acceptable for the market. In this way, she will increase her revenues, but place the supply chain in a point far from the optimum or definitely disrupt the chain.

5. Conclusions

Cooperation for the common good and potential conflict of interests are two major features of business coalitions. The notion of coordinating actions between suppliers and resellers in order to optimize some coalition-wide cost function (a common good) is at the basis of supply chain management. However, knowledge sharing may also allow for individual coalition participants to evaluate (e.g., computing a fairness function) to which extent the common good will keep them away from their individual objectives. In this paper we argue that if this distance is too great, knowledge sharing will backfire: individuals will adopt uncooperative behaviour to push the coalition back to a situation fairer to them, moving away from the common good. A risk assessment methodology can be based on such consideration and uncooperative behaviour can be prevented by knowledge obfuscation and secure computation, in order to preserve the common good.

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