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THEORETICAL FOUNDATIONS FOR IMPEMENTING INCENTIVE COMPATIBILITY IN SUPPLY CHAINS GOVERNED BY INFORMATION ASYMMETRY

A.K. Lazaris,
[†] Business College of Athens, Computer Science Department. 4, Dimitressa Str. 11528 Athens, Greece

P.H. Yannakopoulos
[‡] TEI of Piraeus, Computer Systems Engineering Department, 12244 Aigaleo, Greece

Abstract
Information asymmetry disintegrates the performance of Supply Chains, by inducing misallocation of the available and potential resources, discriminatory pricing and allocation policies leading to winners and losers in the wealth creation game, arbitrage, lead-times variations and unpredictability. We provide the theoretical underpinning that can reinforce truthful information sharing, that is an *incentive compatible mechanism*. We focus on scenarios about allocating the capacity of a supplier. An implementation of the mechanism was presented in the form of SSCC protocols by Lazaris (2008). Managerial implications are issues for further discussions.

Keywords: truth-telling; information sharing; capacity allocation; supply chain management

LITERATURE REVIEW

1.1. The Concept of information asymmetry. Information sharing and the value of shared Information.

In Economics, *information asymmetry* can be defined as the phenomenon in which all players (called *agents* as well) do not own the same information related to a transaction they intend to participate in, at the time the decisions must be made. This phenomenon was initially studied by the Nobel laureates Arrow (1963) and Akerlof (1970). The latter stressed that the average value of commodities are apt to disintegration, even for those that are of best quality.

A cardinal reason of the presence of information asymmetry is the embedded apprehension that private individual information may leak to other stakeholders/competitors.

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This coerces them not to pursue policies consistent with a framework that encompasses information sharing, collaboration and trust. Indeed, Li (2002), after studying the effects of vertical information sharing between a supplier and a number of retailers, has concluded that the major obstacle to information sharing exceeds the technological barriers.
The repercussions of this phenomenon, which were mentioned in the introduction, have been expanded covering the full spectrum of business activities (Corbett and de Groote 2000; Corbett et al. 2004, and Iyer et al. 2005). Besides, the Bullwhip Effect[1] can be reinforced by information asymmetry.
Information sharing as an alleviating method against information asymmetry has been identified by researchers, among of who are Hsieh et al. (2006). From a managerial perspective, information sharing can enhance market orientation (Baker and Sinkula 1999) and form synergies (Burt et al. 2003; Fiala 2004). Furthermore, the numerical study by Cachon and Fisher (2000) shows a reduction to supply chain costs when information sharing takes place. Lambert and Cooper (2000) interconnect information sharing and collaboration with the entire supply chain's processes integration.
Significant successful ventures that are based on information sharing are VICS' "Collaborative Planning, Forecasting and Replenishment" (CPFR) and SAP's VLM. Different "signals" from all participants are amalgamated with their privacy, which is always an objective.

Computer Science's Secure Multi-Party Computation (SMC) is recently applied to supply chain management. It is often called "Secure Supply Chain Collaboration" (SSCC), where all players can share information for the computations, but their individual information remain private. Specifically, the properties of SSCC protocols apart from *privacy* involve *integrity* -i.e. inputs cannot be modified by unauthorised players-, *correctness* of the results/outputs and fairness -i.e. dishonest players will be excluded.

1.2. Incentive Compatibility in Mechanism Design

Incentives can be categorised as remunerative (financial), moral and coercive. The elements of an incentive problem are three: The stakeholders (their information and their potential strategies), the mechanism and its objective. Due to the unpredictable response to incentives, the design must provide an unambiguous mechanism, where all issues towards the final payoff are clarified. A mechanism is incentive compatible when honesty and obedience is an equilibrium (in terms of Game Theory), that is no participant player can achieve better by being dishonest or by disobeying. Our proposal is an incentive compatible mechanism focusing on remunerative incentives: profit maximisation when telling the truth.

[1] Demand variability increases while we move upwards the supply chain. Small demand variances may imply larger variations in the orders placed upstream.

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Furthermore, we pillar Distributed Algorithmic Mechanism Design (DAMD)[2] framework (Feigenbaum et al. 2002), adding privacy of the players' information and combining distributed players with centralised decision-making.

1.3. Capacity Allocation

The problem of allocating a supplier's capacity is fundamental. Management Science has become dependent on Computer Science and IT's facilitations in order to perform better, reduce costs, increase profits and provide a more fair and unbiased market environment. Besides, McGarvey and Hannon (2004) recognise the optimal allocation of resources as a principal factor for achieving the goals of the business. The reasons for undertaking an allocation strategy based on IT (e-allocation) can be distinguished by the "*7C*s": Capability, Control, Connectivity, Cooperation, Cost, Competitiveness and Creativity. We will not discuss these categories in this report. However, it is apparent that an allocation strategy is facilitated by IT manifoldly.

There are a number of issues that prevent capacity allocation methodology in supply chains from becoming a dynamic system where all direct and potential players can contribute to the final result (in a direct or an indirect manner). These issues include lack of incentive compatible mechanisms, lack of mathematically established framework that allows all players to share (input) individual private information that affect the final outcome, lack of mechanisms that resolve discriminations among players, lack of utility tools that are based on all these and simultaneously incorporate privacy and security issues. Our proposal moves towards the elimination of these obstacles.

The focus will be on two capacity allocation mechanisms, the *linear* and the *proportional*. We focus on a *two-tier* supply chain model, which encompasses a *monopolistic* supplier whose capacity is fixed, say K (i.e. consists of K indistinguishable units of an item), and a finite number $N \geq 2$ of independent retailers (or manufacturers). The demand curves of retailers are based on the price they charge. Retailers' benefits are dependent on a number of factors, among of which are the position the have on their downstream markets, the price at which they can resell their commodities, etc. The forms of the demand curves, excluding their parameters (e.g. mean market demand), which remain private information, are known to everyone. A Mechanism Design will attempt to design a framework that on one hand maximises the profits for supplier, whose *all* capacity will be allocated, and on the other allows the retailers to choose the *types* that maximise their own expected profits, without revealing the retailers' private information. This mechanism will be a composition of a pricing mechanism along with a capacity allocation mechanism, both set by the supplier, which will provide incentives (*incentive compatible mechanism*) to retailers to announce their true *types* θ_i to the supplier, i.e. the

[2] It is an amalgamation of incentive compatible mechanism design and computation tractability. The participants and their information are distributed.

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parameter or signal that determines agent *i*'s *preference*, maximising their respective profits. In terms of Management, the mechanism can be considered as a means to applying to some extent a "*pull*" model of management. Because of the fixed, finite capacity of the supplier, and the decision strategy to maximise profits, Dai et al. (2006) would describe this model as a relevant to *revenue management*.

It is mathematically proved that, when the orders of the retailers are based on *continuous demand curves*, the optimal capacity allocation mechanisms for the supplier are the *linear* and the *proportional*. The appropriate choice of one of these two mechanisms has been a matter of critical attention, especially when considered in terms of Mechanism Design or whether the supplier has a prior of retailers' orders, and the various profit repercussions. For instance, management scientists have concluded that, when retailers face a *newsvendor* problem, that is a *stochastic* (probabilistic) demand:

- If the demand distribution is *normal*[3] with mean $\langle\theta\rangle$, with an *exponential* prior (on θ), then linear allocation is optimal for the supplier.
- If the demand distribution is *uniform*[4] on $[0,\theta]$ with *Pareto* prior, then proportional allocation is used by the supplier for individual optimality. (Maskin and Riley 1990)

The continuous demand curves are described by the common equation: $q=\theta_i-p$ or $p=\theta_i-q$, where q and p are the market demand and the retail price respectively, and θ_i is the market demand if price equals zero, called *market potential in retailer i's market*.

The *pricing-and-allocation policy* (*mechanism*) that will be used can be denoted as $\{P(\theta_i),Q(\theta_i,\theta_{-i})\}$. As far as θ_{-i} is concerned, it is $\theta_{-i}=\theta_1\times\cdots\times\theta_{i-1}\times\theta_{i+1}\times\cdots\times\theta_N$. (to describe a combination of types for all individuals other than *i*.

The purchasing cost $P(\theta_i)$ of retailer *i* is based on their announced individual type. The quantity-allocation function $Q(\theta_i,\theta_{-i})$ is depended on the private information parameter θ_i of *i*-retailer, but also the values of the others, called θ_{-i}.

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[3] It is a continuous probability distribution and, if σ^2 is the variance, its *probability density function* (*pdf*) f will be:

$$f(\theta)=\frac{1}{\sigma\sqrt{2\pi}}\cdot\exp\left[-\frac{(\theta-\langle\theta\rangle)^2}{2\sigma^2}\right].$$

[4] When it is a discrete probability distribution where all the values of the set of *n* possible values are equally probable. Their probability is $\frac{1}{n}$. In case of a continuous probability function, if $\underline{\theta},\overline{\theta}$ are the margins of the set of possible values, then the *pdf* will be $f(\theta)=\frac{1}{\overline{\theta}-\underline{\theta}}$.

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The general framework of the *direct revelation mechanism* for the implementation of the pricing-and-allocation policy can be described by the following steps:

- Set of pricing-and-allocation policy by the supplier.
- Announcement of each retailer's type, which will maximise its respective profit, given the supplier's price-and-allocation policy. Specifically, the its objective is the maximisation of the quantity: $\pi_i(x,\theta_i)$, i.e.:

  $$\max_x\left[\pi(x,\theta_i)\right]=E_{-i}\left\{R\left[Q(x,\theta_{-i}),\theta_i\right]-P(x)\right\}$$

  where x is the announcement of the type of retailer *i*, and is picked from the set of possible θ: $x\in\Theta\equiv\left[\underline{\theta},\overline{\theta}\right]$, and $\underline{\theta},\overline{\theta}$ are the minimum and the maximum values of θ respectively, and Θ is the set of possible types. In terms of *Mechanism Design*, the policy is incentive compatible if $x^*=\theta_i$, namely the best choice for each retailer is to announce its true type.
- Implementation of the policy, based on the types announced.

We provide a theorem under of which a policy/mechanism becomes *implementable*, i.e. it is incentive compatible and provides non-negative profits to the retailers, and another one defined by Maskin and Riley (1990), which specifies the optimal type of mechanism selected by the supplier.
These theorems are stated below, and the proof of the first can be found in Lazaris (2008).

Theorem 1
The Pricing-and-Allocation mechanism $\left\{P(\theta_i),Q(\theta_i,\theta_{-i})\right\}$ *is incentive compatible if and only if conditions (1) and (2) hold. In addition, condition (2) is sufficient (n.a.s.c.) to guarantee non-negative profits (non-negative payoff values) for the retailers.*

$$\int_x^{\theta_i}E_{-i}\left\{R_\theta\left[Q(x,\theta_{-i}),\theta\right]\right\}d\theta\le\int_x^{\theta_i}E_{-i}\left\{R_\theta\left[Q(\theta,\theta_{-i}),\theta\right]\right\}d\theta$$

$$P(\theta_i)=E_{-i}\left\{R\left[Q(\theta_i,\theta_{-i}),\theta_i\right]-\int_{\underline{\theta}}^{\theta_i}R_\theta\left[Q(\theta,\theta_{-i}),\theta\right]d\theta\right\}$$

Theorem 2
If retailers face deterministic downward sloping linear demand, with the intercept of the downward-curve θ private to the retailers, then the linear allocation mechanism is optimal for the supplier.

The *Linear Allocation Mechanism* will be presented briefly.

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Let the retailers be ordered in a decreasing way, say $q_1 \geq q_2 \geq ... \geq q_N$. If we call $\bar{n}$ the number of the retailers who will buy in the end, K is the (fixed) total capacity of the supplier, then the allocation $Q(q_i, \bar{n})$ to retailer *i* will be:

$$Q(q_i,\bar{n}) = \begin{cases} q_i - \frac{1}{\bar{n}} \max\left[0, \left(\sum_{i=1}^{\bar{n}} q_i\right) - K\right], \ i \leq \bar{n} \\ 0 \text{, otherwise} \end{cases}$$

Note that $Q(q_i, \bar{n}) \geq 0, \forall i \leq \bar{n}$.

Commenting on the nature of linear allocation, we can describe it as an "*equal sharing of pain*" among the retailers that will actually buy, defining as pain the fixed quantity $\mu = \frac{1}{\bar{n}} \max\left[0, \left(\sum_{i=1}^{\bar{n}} q_i\right) - K\right]$.

On condition that the "pain" does not exceed the q_i of the retailer-buyer *i*, he/she suffers the same amount of pain, namely each of the buyers gets its ordered quantity minus a fixed quantity, which is the so-called "pain".

In the *Proportional Allocation Mechanism,* if N is the total number of retailers, the allocated quantity to retailer *i* is:

$$Q(q_i, N) = \min\left\{ q_i, \frac{Kq_i}{\sum_{i=1}^{N} q_i} \right\}$$

It is apparent that in this case it is $\bar{n} = N$, which means that *every* retailer becomes a buyer, namely a quantity is always allocated to each of them.

From the equation above we can derive that the quantity allocated equals the quantity ordered when the sum of all orders does not exceed the capacity of the supplier.

1.4. Plausible questions, tangible reality

1.4.1. Why truth-telling?

Previously, we mentioned the importance of the choice of the appropriate capacity allocation mechanism. A parameter that reinforces increased attention is the effect of truth-inducing mechanisms and whether they are (or can be) incentive compatible. Indeed, there are approaches, sometimes contradictory to each other, that support one or another choice. Suggestively, on one hand there is the approach of Cachon and Lariviere (1999) according to which truth-inducing mechanisms are not a universally desirable goal, since they can lower the profits for the supplier, even the retailers. Besides, in the case where the sum of retailers' orders

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exceeds the capacity of supplier, the retailers receive less than their orders, if a linear or a proportional capacity allocation mechanism is used. This non-universality is also supported by *Gibbard-Satterthwaite theorem* (Gibbard 1973 and Satterthwaite 1975). In terms of *dominance*, truth-telling is not a dominant strategy under individually responsive allocation mechanism, according to them. Cachon and Lariviere (1998, 1999) demonstrate that, when a linear or a proportional allocation mechanism is used, the retailers have an incentive to order *strategically*, that is inflate their orders, in an attempt to ensure that the allocated quantity will be closer to what they really want. Their numerical study indicates lower profits for the supplier as much as 19% if truth-telling induced by uniform allocation[5] is not used and replaced by IR allocation mechanisms (linear) that induce over-ordering (namely dishonesty). On the other hand, Deshpande and Schwarz (2002, 2005) managed to confront and contradict this providing a numerical study. Indeed, according to this study both supplier and supply chain profits can have an astonishing comparing increase of a minimum 842%, if the optimal truth-telling allocation mechanism replaces a manipulable one. This precedes the restrictive and seemingly unique truth-telling choice of uniform allocation. as described by Cachon and Lariviere (1998).

1.4.2. Why it is so important for retailers to keep their θ private.

The profit-maximising quantity of retailer *i* is $q_i = \theta_i/2$, where θ is the demand, if price equals zero ("*market potential*")

The general equation of the P-Q relation is: $p = \theta - q$, thus the mathematical expression of profit, which is $\pi = p \cdot q$, will be $\pi = (\theta - q)q = \theta q - q^2$.

The maximum (*extremum*) of $\pi(q)$ holds when $q = \theta/2$, and it is $\pi_{\max} = \theta^2/4$. Indeed, $\pi'(q) = 0 \Rightarrow \theta - 2q = 0 \Rightarrow q = \theta/2$. □

This entails that the supplier can elicit retailers' private θs if these remain steady during a period of repeated orders. Consequently, retailers would be reluctant to make new orders, since their private information would be exposed.

Acting rationally, a retailer would order a quantity of $q = \theta/2$ units, and, of course, (try to) sell all this quantity at the price of $p = \theta - q = \theta - \frac{\theta}{2} = \frac{\theta}{2}$.

- If the purchasing price per unit equals the price he/she sells, that is $\theta/2$, he/she will have no profit.

[5] that is $Q(q_i, N) = \begin{cases} q_i \ , \ \sum_{i=1}^{N} q_i \le K \\ \min\left\{q_i, \dfrac{K}{N}\right\}, \ \sum_{i=1}^{N} q_i > K \end{cases}$

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- If the purchasing price per unit exceeds $\theta/2$, he/she will have a loss, and
- If the purchasing price per unit is less than $\theta/2$, he/she will have a profit.

Apparently, the maximum price per unit a retailer would accept to buy at would be $\theta/2$. For this reason, the supplier would charge retailer a price $\theta/2$ per unit, when having unlimited capacity (i.e. the condition $\sum_i q_i \le K$ holds. In this case, the quantities allocated are equal to the quantities ordered. Consequently, the supplier can infer retailers' θs.), and, thus, capture all the retailer's profit, or allocate the limited capacity K in such a way that the marginal revenues are equal across all retailers, gaining all the retailers' profits. The same objectives also hold when the supplier is aware of a probability distribution on θ for each and every retailer. However, the adhered uncertainty entails a profit margin for the retailers despite the supplier's approximation of $\theta/2$.

1.4.3. Facing the danger of Price Discrimination

The disclosure of this sensitive information emerges *Pigou's Three Degrees of Price Discrimination*. In the first, the supplier charges a different price for every sale, in the second they charge different prices for different quantities and in the third retailers are separated based on easily identifiable characteristics (*segmentation of market*).

1.4.4. The application of the Revelation Principle

Such scenarios, which are related to inverse optimisation, can erode, and, most presumably, ruin any framework of incentive compatibility. The allocation mechanisms described above require the truthful revelation of all parameters in order to be optimal, based fundamentally on the *revelation principle* according to which, when information asymmetry governs a game, any equilibrium outcome with a mechanism has a corresponding revelation mechanism that ends up to equilibrium, where all the agents truthfully report their private types. Regularity conditions (e.g. continuity, etc.) transmitted and conferred via the revelation principle are thoroughly discussed by Kojima (2005). Due to them, the limits of the revelation principle are elucidated.

It is apparent that the fundamental objective of any secure capacity allocation protocol is to prevent the revelation of private information to any stakeholder (that may take advantage of it). This will be part of the discrimination of *decision-making* from *implementation*. In this allocation scenario, the decision-making process is the allocation decision, and the implementation process is the supplier's capacity allocation to the retailers. Separating these processes means that the supplier must *be told* how to allocate his fixed capacity K to the $\bar{n}$ retailers that will finally buy.

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1.5. No room for Agency Loss

The four preconditions that must be met in order the convergence of the actual and the optimal outcome to be achieved are addressed due to the following reasons:

- The Price-and-Allocation mechanism is given, establishing a commonly acceptable framework to all players.
- It does not have an interest neither discriminates (neutral). It focuses on the maximisation of their respective profits.
- The incentive compatibility and the privacy of their private information are embedded.

2. (A FEW) FINAL THOUGHTS. INCENTIVE COMPATIBILITY: SCIENCE FICTION? SCIENCE FACT.

Information asymmetry is a pervasive and eroding phenomenon in the supply chain. The roots of information asymmetry are intricate, having ramifications throughout the entire system of the supply chain. Decision-making is strictly dependent on the type, the quantity and quality of any relevant information. The locus of studies -most of which are based on the common sense- is that in order for the supply chain to operate and perform successfully and as an optimised process, the dissemination of accurate information is considered more than important. This requires the convergence and conglomeration of the individual interests of the stakeholders. This summons the development of corresponding methods/mechanisms that ensure optimal results (for all stakeholders), combined with credibility and privacy for all the used information (at least the information that can be exploited by one's competitors if revealed). Using the traditional methods, such issues seem elusive, especially in cases where the sender has incentives to distort the sending information in order to manipulate the information needed for the final decision/result.

Focusing on eliminating information asymmetry in capacity (stock) allocation problems, we designed an incentive compatible mechanism that allows retailers to announce their true types (truth-telling), towards the maximisation of their respective profits. Simultaneously, the supplier can choose his/her optimal capacity allocation method (linear or proportional). The general framework can be epitomised as a centralised collaboration and information sharing of decentralised (distributed) players, where the desired outcomes are achieved through a sincere revelation of the critical private information, while that information remains private even if it is used in the computations.

We focused on the issue of the allocation of a supplier's capacity, and, for simplicity reasons, we studied the allocation of the fixed capacity of one monopolistic supplier that sells to a number of non-competing retailers. The consistency between theory (incentive compatible mechanism) and practice (prototypes) (Lazaris, 2008) denotes that the alignment of strategy towards an e-

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allocation adoption using web-applications is feasible, and amends the supply chain manifoldly. The development of these prototypes also proves that tools for eliminating information asymmetry, its consequences and all potential discriminations among the players can be created and used. Strict security throughout the entire process strengthens the incentives for adopting such e-approach.

Further amendments may include an expansion to more suppliers, as well as additional capacity allocation methods, like "*price-quantity ordering*" ("*pick-and-choose*") and *market clearing transactions* with non-discriminatory pricing (*uniform price auctions*). Furthermore, all issues of inverse optimisation must be resolved, since they are deterrent factors for the unambiguous adoption of e-allocation applications. Unfortunately, there is one condition that cannot be overcome: When the sum of all orders do not exceed the supplier's capacity $\left(i.e. \ \sum_{i=1}^{N} q_i \leq K \right)$, the allocated quantities equal their individual orders $(i.e. \ Q_i = q_i)$. In that case, the supplier can infer their market positions, assuming that they order on the basis of maximising their respective profits $\left(q_i = \frac{\theta_i}{2} \Leftrightarrow \theta_i = 2q_i \right)$. However, all retailers are allocated their desired quantities.

At the time being, we do not have a solution to that problem. We should mention that the same obstacle remains even if we used decentralised approaches.

The adoption by Toshiba (DP Solutions, 2008) of methods familiar to our approach is a very promising fact. Besides, it is all about greater profitability. It is the fundamental driving force, isn't it?

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