Encouraging suppliers to process innovations: a game theory approach

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Abstract: This paper studies the design of process-innovation incentives in supplier networks. A real-life case study from the boat-building industry is presented to illustrate the importance of explicitly encouraging suppliers to continuous improvement. Motivated by the case study, we constructed a game theory model trying to capture the possible conflicting interests of different parties in a company network. Using our model, we applied three different bargaining rules in order to determine *ex-ante* profit-sharing principles that award process-innovations. The aim of profit sharing is that the efficiency-improving arrangements can be implemented so that none of the network companies has to incur losses. Consequently, if the profit-sharing principles are *ex-ante* contracted, then the network companies have the incentive to innovate.

Keywords: innovation; network; incentive; game theory; profit sharing; demand supply chain management.

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1   Introduction

For companies operating in dynamic and competitive fields of business, collaborative supplier networks are becoming a necessity rather than a mere advantage. The business is moving towards a state where, instead of individual firms, the networks of companies compete against each other. This phenomenon enables efficient outsourcing, thus allowing individual firms to focus on their core competencies (see *e.g.*, Nooteboom, 1999; Dyer, 2000).

The trend of increasing collaboration in supplier networks calls for up-to-date models that support the decision-making of management in firms engaged in the network economy. The need for models and practices for interfirm relationships has been brought out by several authors. Recently, Cousins and Spekman (2003), Lei (2003), and Gertsen (2003) have suggested that there is a growing need for models that encourage suppliers to innovate. Accordingly, the objective of this paper is to study explicit mechanisms that can be utilised as process-innovation incentives for the suppliers. By process innovations we denote operations that lead to efficiency improvements, for instance in supplier networks.

The networked companies make their decisions in conditions where companies aim at win-win situations with their network partners, but simultaneously endeavour to improve their own benefits individually. In consequence, the interests of separate network companies may be partially conflicting, despite the common objective of global efficiency. This motivates the utilisation of game theoretical concepts in the analysis of decision-making in networked economy (see *e.g.*, Nalebuff and Brandenburger, 1996; Nooteboom, 1999; Pearson, 2003).

We utilise game theoretical modelling to study the design of process-innovation incentives for supplier networks. In this paper, process-innovation incentives denote the guarantee of joint gains among the network companies whenever the total efficiency of the network increases. In general, earlier literature concerning innovation-incentive mechanisms is mostly concerned either with the national level (*e.g.*, Jaffe, 2000; Conceição *et al.*, 2003; Kuhlmann and Edler, 2003) or with the intra-firm level (*e.g.*, Leptien, 1995; Nerkar *et al.*, 1996; Bester and Petrakis, 2004). However, the research on innovation incentives for company networks has been scarce. Also game theory applications to innovation systems have been few. One such is that of van der Meulen (1998), who studies national science policies.

This paper contributes to the existing literature in several ways. First, our model suggests that a win-win situation is possible indeed, whenever a process innovation is implemented. Second, we present the explicit design of process-innovation incentives for supplier networks. Based on game theory, we analyse three strategies for utility sharing, which can be utilised to encourage the suppliers to innovate. Third, earlier models on supplier network management were usually concerned with the issue of clients and

suppliers. In addition, our model captures the relationships between the suppliers as well. The model is motivated by a case study concerning the supplier network of a Finnish luxury sailing-yacht manufacturer Nautor Ltd.

The rest of this paper is structured as follows. Section 2 reviews earlier game theoretic studies on enterprise networks. Section 3 describes the case study and presents a game theoretic model which suggests that the possibility of a win-win situation exists whenever the efficiency of the network is improved. Section 4 presents three different bargaining solutions that can be applied as process-innovation incentives for suppliers. In Section 5, we illustrate the use of the model with a numerical example. Section 6 discusses the characteristics of our model, and the conclusions and suggested topics for further development are in Section 7.

2 Recent literature on company networks

During the last decade, game theoretic applications on interorganisational relationships have become popular. For example, Wolters and Schuller (1997) developed a dynamic game theory model in order to study how trust can be forged in a supplier-client relationship. In their model, both players repeatedly have the opportunity to behave opportunistically, which terminates the partnership but yields benefit for the opportunistic party. The utility to both players grows sustainably as the game continues without exits. Wolters and Schuller conclude that in order to foster trust it is beneficial for the client to have fewer suppliers who are encouraged to engage in R&D cooperation with the client. The suppliers are rewarded by longer contracts, which provide economical stability and an implicit incentive for value-adding innovations.

Lim (2001) studied quality control between the client and supplier when the client has incomplete information on the quality of the supplied product. Lim considers two contracting schemes:

1   the client receives a price rebate when defect products are detected

2   a warranty agreement.

The paper presented optimal contracting strategies when the aim was to maximise the expected profit of the client, regardless of the supplier's profit.

Corbett and DeCroix (2001) studied supplier incentives in the situation where the client is supplied with indirect materials. Indirect materials, *e.g.*, paint or other chemicals, are not directly related to the final product, but are necessarily consumed at some point of the manufacturing process. In consequence, the client wants to reduce the use of the indirect material, whereas the supplier's profits depend on increasing volume. Corbett and DeCroix analysed several contracts that motivate the supplier to cooperate with the client, aiming to reduce the consumption of the indirect material. Game theoretic analysis shows that such contracts can always increase the profit of the supply chain, but do not necessarily result in reduced consumption. Corbett and DeCroix also conclude that generally it is not feasible to reduce consumption and increase profits concurrently.

Cousins (2002) presented a conceptual game theoretic model that can be utilised to analyse strategic relationships. The paper also included an extensive literature review. Cousins suggested that relationships should be viewed as processes rather than entities. Moreover, the relationship process has to be exploited primarily to create additional

value. The model presented in the paper focuses on two dimensions of relationships, namely, dependency and certainty between the partners. The output of each relationship process needs to be viewed in the light of these two dimensions. Thereby, it should be considered whether the output of the process is in line with the obligations and risks of the relationship.

Ginsburgh and Zang (2003) examined a situation where a syndicate of service providers offered the customer a limited-time access pass to their services. In this case, the syndicate consisted of several museums around the globe. The customer paid the syndicate a fixed amount, independent of the usage of the services. In their paper, Ginsburgh and Zang suggested that the Shapley (1953) value mechanism be used in sharing the profit from the passes among the members of the syndicate.

Brocas (2003) built a model for studying the vertical integration of two innovator-producer pairs with competing technologies. Both innovators are willing to licence their technology to a downstream producer, who enters a Cournot competition with the other producer. Brocas solved the game model for equilibrium and found out that when the technology switching-costs for the producers are high, it may be profitable for the innovators and producers to integrate vertically. The paper also brings out the social benefit: the vertical integration may increase the probability that the more efficient technology survives and becomes a standard.

Kamrad and Siddique (2004) approach the supplier network management by portfolio theory. The objective is to form a portfolio of suppliers minimising the total exchange rate volatility. Their model uses real-option theory in order to capture:

- the suppliers' reactions to the client's profit-maximising behaviour
- the client's option to switch suppliers.

In addition, Kamrad and Siddique use sequential bargaining to find a contract agreement between the suppliers and the client.

Our paper contributes to the existing literature by considering explicit methods for encouraging the suppliers to nonprogrammed process innovations.

3   Process-innovation incentives for supplier networks

3.1   Background of the case study

This paper is based on a case study on the Finnish luxury sailing-yacht manufacturer, Nautor Ltd. The company operates in the neighbourhood city of Pietarsaari at the Gulf of Bothnia, with a staff of some four hundred employees. Nautor has recently launched the production of a new type of racer-cruiser, the Swan 45, which is the first one-design yacht of the company. Earlier, the yachts manufactured by Nautor have been greatly customised to the needs of the customer. However, Nautor's vision with the Swan 45 was to found a racing class for this specific yacht, thus requiring the uniformity of the Swan 45'ers.

Also the construction process of the Swan 45 was novel for Nautor. The yacht was being built modularly in a supplier network located in the same region as Nautor's yard. A crucial requirement for the outsourcing was the one-designness of the yacht, since now the client (Nautor) would not need to deliver individualised blueprints of each yacht to the supplier network. This enabled, for instance, the serial production of some parts, which made the manufacturing process efficient.

The researchers of VTT Technical Research Centre of Finland closely participated in accumulating and developing the supplier network. The person responsible for the network project at Nautor was a development director who had a background in economics. The detailed description of the network can be found in Salkari and Simons (2004). Instead of describing the whole project, the focus of this paper is in finding mechanisms that support the further development of a supplier network in general.

3.2   Definition of process innovation

Consider a company network that consists of a client and several suppliers. The network forms a supply chain in which each of the companies carries out a specified task, which is part of the manufacturing of a final product. In this environment, a *process innovation* is an idea that is implemented and leads to improvement in the efficiency of the manufacturing process. Furthermore, the efficiency improvement can lead to cost reduction or improvement in quality, for instance (*e.g.*, Knight, 1967).

When aiming at global efficiency, all the members of a network should innovate. Recalling the case of Nautor, after the supplier network had been accumulated, the main objective of Nautor was to reduce the production costs of the network. In practice, this may occur in several ways. For instance, consider the following case.

Among others, there are two suppliers essential to this example: a hull manufacturer and a Heating, Plumbing and Air-Conditioning (HPAC) installer. In the construction of the very first Swan 45'ers, the HPAC installer himself drilled holes for the pipelines into the ready-made hull. Drilling the holes was time-consuming, since the drillman had to work in a constricted space and in uncomfortable positions. The striking change was to transfer the drilling of the holes from the HPAC installer to the hull construction, where the work could be done before the hull was assembled. This transfer of work reduced work load related to the drilling. Such efficiency improvements as that in the previous example are usually referred to as process innovations.

3.3   The model of process innovation

The motivation for the *game theoretic* study of process innovations in supplier networks arises from the hypothesis that despite the network's common goal of joint gains, the objectives of individual firms are partly conflicting. Such circumstances are often analysed by the means of game theory (see *e.g.*, Parkhe, 1993; Nalebuff and Brandenburger, 1996; Nooteboom, 1999).

The problem of cases similar to the example in the previous section is that the suppliers' work loads change. This raises the need to change the supplier payments. First, the supplier whose work load increases (the hull constructor of the example) probably claims for compensation. Second, the natural way to finance this compensation is to reduce the payment of the supplier whose work load decreases (the HPAC installer). Third, the client also wants a share of the cost savings in order to gain competitive advantage against competitors' improvements in their performance. In addition, in order to encourage the network to continuously innovate, the individual companies of the network should be guaranteed at least a no-loss situation whenever a process innovation is implemented. Otherwise, if there is a fear of loss, the network companies might be unwilling to bring out ideas that could improve the efficiency of the network as a whole. This dilemma is usually referred to as the moral hazard.

Our approach to the problem is *ex-ante contracting*. The idea is that, if all parties can be guaranteed an increase in benefit whenever a process innovation is implemented, then the companies have the incentive to innovate. In the following, we shall construct a game theoretic model that captures the case.

The players of the game are $N = \{1,..., n\}$, where indices $N_s = \{1,..., n-1\}$ denote the suppliers and n is the client. In the status quo, a supplier $i \in N_s$ performs work, for which he receives a positive payment p_i from the client n. Let υ_i denote the supplier's non-negative costs for the work (consisting of labour costs, material costs, *etc.*). Hence, the profit for a supplier $i \in N_s$ is:

$$\text{profit}_i = p_i - \upsilon_i.$$

If the supplier i's work load changes, then we let Δv_i denote the corresponding change in i's costs. Furthermore, let Δp_i denote the change in i's fixed payment that the client would conduct due to the change in work load, and let $\mathbf{\Delta p}$ denote the vector $(\Delta p_1 \cdots \Delta p_{n-1})$. The change in the supplier i's profit is then

$$\pi_i = \Delta p_i - \Delta \upsilon_i, \quad \forall\, i \in N_s. \tag{1}$$

Since the client n makes the payments Δp_i to the suppliers $1, \ldots, n-1$, the change in the client's profit is

$$\pi_n = -\sum_{i=1}^{n-1} \Delta p_i. \tag{2}$$

We let Equation (1) denote 'the utility to the suppliers' $i \in N_s$ and Equation (2) denote 'the utility to the client' n. Hence, in the status quo all the players' utilities are equal to zero.

We present the problem as a two-stage game (see Figure 1). In the first stage, the client (player n) defines a utility-sharing rule ϕ, by which the suppliers' payments (p_i's $\forall\, i \in N_s$) will be redefined if the suppliers' costs (c_i's) change due to a process innovation. Hence, the set of (pure) strategies available to the client n is the family F of functions which map the changes in the suppliers' costs (the Δv_i's) to changes in the payments (the Δp_i's):

$$\phi \in F, \quad F = \{\phi \mid \phi : \mathbf{R}^{n-1} \mapsto \mathbf{R}^{n-1}\}.$$

Let ϕ_i denote the rule that concerns supplier i, *i.e.*, $\Delta p_i = \phi_i$.

In the second stage of the game, one or more of the suppliers $1,..., n-1$ discover(s) an efficiency-improving option. The implementation of the idea would improve the efficiency of the network but would also require transfer of costs inside the network. Knowing the utility-sharing rule ϕ, the supplier may now choose his strategy c_i between coming up with the idea ($c_i = a$) or withholding the idea ($c_i = b$). Let us denote the set of strategies available to the suppliers $i \in N_s$ by $C_i = \{a, b\}$.

Figure 1 Game in the extensive form
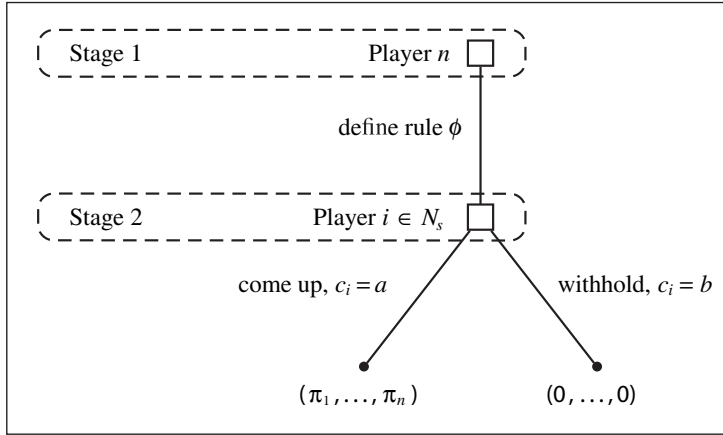
The process-innovation game in its *strategic form* is:

$$\Gamma = (N,(C_i)_{i \in N_s},\phi,(\pi_i)_{i \in N}) \tag{3}$$

where:

N = is the set of players N = {1,..., n}.

N_s = is the set of suppliers N$_s$ = {1,..., $n-1$}.

C_i = is the set of strategies available to the suppliers $i \in N_s$, $C_i = \{a, b\}$.

ϕ = is a function ϕ: $R^{n-1} \mapsto R^{n-1}$, which denotes the strategy of the client n, *i.e.*, the utility-sharing rule.

π_i = denotes the utility to player $i \in N$. For the suppliers $i \in N_s$, π_i is defined in Equation (1) and for the client n, π_n is defined in Equation (2).

In Stage 1, the client n may act as a Stackelberg leader and try to choose his strategy ϕ in such a way that the suppliers $i \in N_s$ are encouraged to propose innovative ideas. In Stackelberg games the players are categorised as leaders or followers. The objective of the leader is to give the follower such incentives that drive the follower to play optimally from the viewpoint of the leader (von Stackelberg, 1934; Başar and Olsder, 1982). It is therefore crucial to the outcome of the game that the suppliers $i \in N_s$ have the information of the rule ϕ at the moment of their decision-making in Stage 2. This can be implemented by an *ex-ante* contract where the utility-sharing rule ϕ is explicitly defined.

In Stage 2, a rational supplier $i \in N_s$ chooses to propose innovative ideas (play $c_i = a$) if the consequences are profitable, *i.e.*, if

$$\pi_i \geq 0. \tag{4}$$

3.4   *Creating a win-win situation through a process innovation*

We formulate the following proposition:

Proposition 1   *A no-loss situation among the members of the network is possible whenever the efficiency of the network is improved.*

Proof: The efficiency of the network is improved if the total costs of the network are reduced. In other words, if the total change in the costs is negative:

$$\sum_{i=1}^{n-1} \Delta \upsilon_i < 0. \tag{5}$$

A no-loss situation requires that the utility to each party is non-negative by Equation 4. First, considering the suppliers' utility (Equation (1)), this implies that:

$$\Delta p_i - \Delta \upsilon_i \geq 0 \quad \Rightarrow \quad \Delta p_i \geq \Delta \upsilon_i, \ \forall i \in N_s. \tag{6}$$

Second, the client's requirement (by Equations (2) and (4)) is that:

$$\sum_{i=1}^{n-1} \Delta p_i \leq 0. \tag{7}$$

If we let $\Delta p_i = \Delta \upsilon_i \ \forall \ i \in N_s$, we then obtain:

$$\sum_{i=1}^{n-1} \Delta \upsilon_i = \sum_{i=1}^{n-1} \Delta p_i \overset{(5)}{<} 0.$$

That is, both conditions (6) and (7) are satisfied, which shows our proposition correct. It is noteworthy, that the total utility derived from the process innovation is:

$$\pi_{\max} = -\sum_{i=1}^{n-1} \Delta \upsilon_i \overset{(5)}{>} 0. \tag{8}$$

This is the surplus utility that can be shared among the members of the network, after the no-loss conditions (6) and (7) are satisfied. Hence, instead of a mere no-loss situation, actually a win-win situation is created.

4   Bargaining solutions as process-innovation incentives

In this section, we apply three different ways to share the surplus utility gained through a process innovation. First, we apply the egalitarian rule, which reflects fairness and complete cooperation within the network. Second, we use the utility-sharing rule according to Nash's (1953) relative threats solution. This, in addition to the egalitarian rule, models the interdependencies between the network companies. Third, the rule according to Harsanyi's modified Shapley value takes into account the possibility of coalition formation inside the network (Harsanyi, 1963). We shall utilise the following definitions throughout the analysis: Let $N_\upsilon \subseteq N_s$ be the set of suppliers whose costs change due to the process innovation, *i.e.*, $N_\upsilon = \{i \in N_s \mid \Delta \upsilon_i \neq 0\}$. Let $n_\upsilon = |N_\upsilon|$ be the cardinality of N_υ.

4.1 Egalitarian solution for the ex-ante contracting

The egalitarian rule implies that the utility-sharing rule ϕ is constructed based on the following two conditions:

$$\pi_n = \pi_i, \quad \forall\, i \in N_\upsilon \tag{9}$$

$$\pi_i = 0, \quad \forall\, i \in N_s \backslash N_\upsilon. \tag{10}$$

In other words, condition (9) says that the suppliers involved in the rationalisation ($i \in N_\upsilon$) and the client n benefit equally. Condition (10) denotes that the other suppliers', whose costs are not affected by rationalisation, payments stay unchanged ($\phi_i = 0 \,\forall\, i \notin N_\upsilon$).

The suppliers involved in the rationalisation ($i \in N_\upsilon$) experience a change in costs ($\Delta\upsilon_i$), which can be positive or negative. Hence, if the client changed each such supplier's payments correspondingly by that amount, the utility to each supplier would be zero, and the client would receive the whole surplus utility from the rationalisation (*i.e.*, π_{max} in condition (8)). However, condition (9) implies that in the egalitarian solution each supplier involved in the rationalisation benefits as much as the client. Hence, in the egalitarian solution, the total surplus utility π_{max} should be shared equally among the suppliers involved in the rationalisation and the client. Therefore, the conditions (9) and (10) imply the following rule ϕ:

$$\phi_i = \begin{cases} \Delta\upsilon_i + \dfrac{\pi_{max}}{n_\upsilon + 1}, & \forall\, i \in N_\upsilon \\[2ex] 0, & \forall\, i \notin N_\upsilon. \end{cases} \tag{11}$$

That is, the suppliers involved in the rationalisation are paid the amount according to the no-loss condition (6) plus a share of the surplus utility (8). This allocation gives each supplier $i \in N_\upsilon$ and the client n an equal payoff of:

$$\pi_i^* = \frac{\pi_{max}}{n_\upsilon + 1}, \quad \forall\, i \in N_\upsilon \cup \{n\}. \tag{12}$$

In game theoretic terms, the allocation (11) is called a *λ-egalitarian solution* since (see *e.g.*, Myerson, 1997, p.382):

- it satisfies the weak efficiency condition

- the player's gains are weighted.

First, weak efficiency guarantees that all the available utility will be shared among the players. Second, conditions (9) and (10) can be interpreted so that the utilities to the players involved in the rationalisation are equally weighted, whereas the weights of the players not involved are zero. Furthermore, solution (11) satisfies the conditions (6) and (7) if $\Delta\upsilon_i$'s satisfy condition (5).

Figure 2 presents the graphical interpretation of the egalitarian solution in a three-player bargaining situation (two suppliers and a client). The feasible region F forms a tetrahedron whose apex concurs with the origin ($\pi_i = 0 \,\forall\, i \in N$), and whose other vertices point to the maximum utilities (8) for each player. The solution (12) is found in the tetrahedron's bottom-triangle centroid, *i.e.*, the intersection of medians.

Figure 2   Feasible region and the utilities of three players
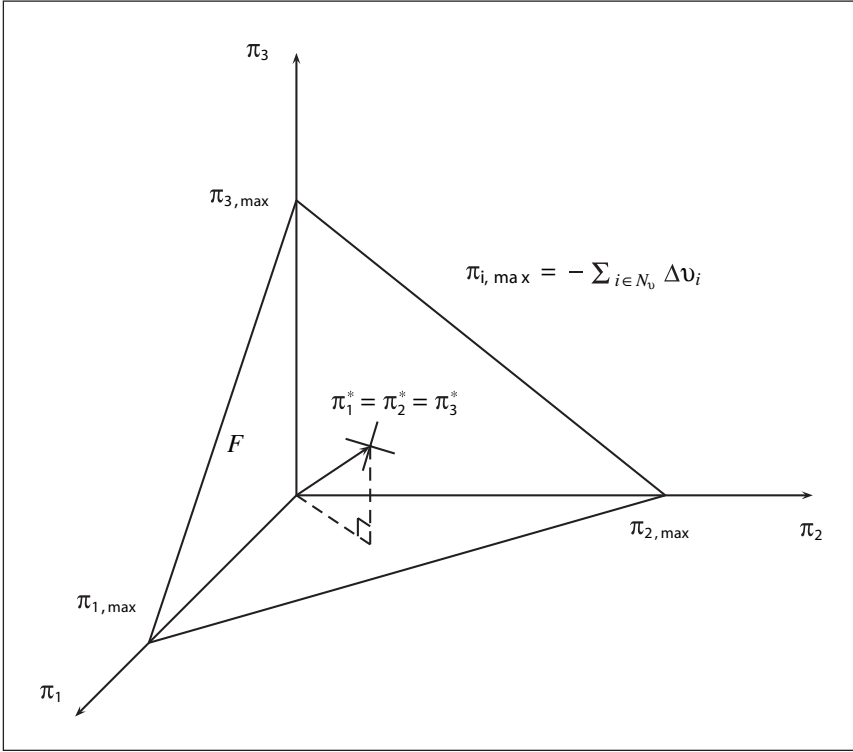
4.2   Use of threats in contract negotiation

It may be fruitful to examine what happens if the suggested alteration in prices is not commonly accepted. Therefore, assume that each player $i \in N$ has an additional possible strategy, threat τ_i, which is the termination of the partnership. If a player executes the threat strategy, the game ends in disagreement. The payoffs to the players in disagreement are denoted by $\tau_1,..., \tau_n$. Since the termination of partnership normally causes additional transaction costs to each party, the τ's are usually negative.

Because of the nature of the game, it is not relevant to consider that the players would threaten each other, unless the game has advanced beyond Stage 2 and the supplier $i \in N_s$, who is making the decision in Stage 2, has decided to come up with his idea, *i.e.*, play $c_i = a$. Thus, Figure 3 expands the game tree of Figure 1 to include the possibility of threatening to terminate the partnership.

Figure 3 Game in the extensive form including threats
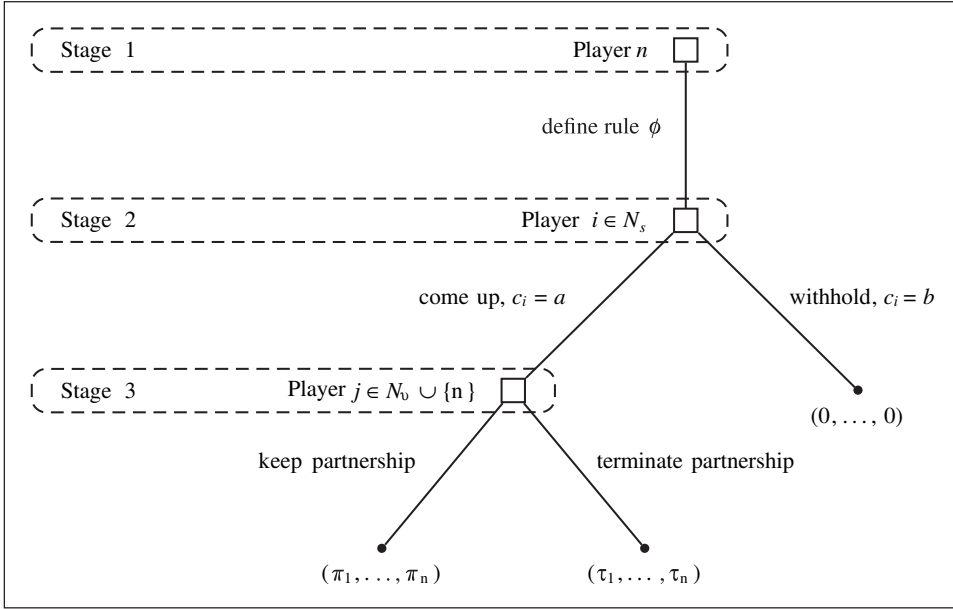
One possible way to take the threat strategies into account is to generalise Nash's theory to *n* players (for two-player games, see Nash, 1953). Mathematically this is straightforward. The Nash product for *n* players becomes:

$$\prod_{i=1}^{n}(x_i - \delta_i),\tag{13}$$

where x_i is the share of utility to player *i* in cooperation, and δ_i is the disagreement payoff to player *i*. The maximisation of the Nash product (13) defines a unique strongly efficient vector **x**, which is the Nash solution to the *n*-player bargaining problem (see Myerson, 1997,p.417).

Hence, the share of utility in the threat game presented in Figure 3 can be defined by the unique strongly efficient vector $\pi \in F$ that maximises the Nash product:

$$\pi^* = \arg\max_{\pi} \prod_{i \in N_v \cup \{n\}} (\pi_i - \tau_i).\tag{14}$$

The maximisation of (14) is equivalent to solving the following conditions:

$$\pi_i - \tau_i = \pi_j - \tau_j \quad \forall\, i, j \in N_v \cup \{n\}\tag{15}$$

$$\sum_{i \in N_v \cup \{n\}} \pi_i \overset{(8)}{=} -\sum_{i \in N_v} \Delta v_i.\tag{16}$$

Condition (15) denotes that the utility to each player is related to the amount of losses in disagreement. Condition (16) takes care that all the available utility is shared.

Conditions (15) and (16) form a linear system of $|N_\upsilon| + 1$ equations containing the same number of unknown variables (the π_i's). Thus, solving the system for π_i's defines vector π uniquely. The utility-sharing rule ϕ can then be calculated from Equation (1):

$$\phi_i(\tau) = \begin{cases} \pi_i(\tau) + \Delta\upsilon_i, & \forall\ i \in N_\upsilon \\ 0, & \forall\ i \notin N_\upsilon, \end{cases}$$

where τ denotes the vector that consists of τ_i's $\forall\ i \in N_\upsilon \cup \{n\}$.

4.3   Coalitions in contract negotiation

4.3.1   Motivation and basic concepts

In Section 3.3, the game model has been constructed for *n* players without considering *coalitions.* However, as the following example illustrates, the need for a coalitional analysis exists.

Recall the example of Section 3.2. There are three players in this game, namely, the HPAC installer {1}, the hull manufacturer {2}, and the client {3}. Let us assume that, in the occasion of a process innovation, the client has proactively decided to apply the egalitarian solution (11) to re-evaluate the payments to Suppliers 1 and 2. Assume further that this is common knowledge (for the definition of common knowledge, see Aumann, 1976).

Suppose that the HPAC installer has an idea of transferring the drilling work to the hull manufacturer. The HPAC installer now has to decide, whether he will bring the possibility of the rationalisation manoeuvre to common knowledge. As a rational player, he will make this decision according to his expectations on the share of the total utility attained by the process innovation (Figure 1). Evidently, a coalition of Suppliers 1 and 2 could be better off leaving the client uninformed of the work transfer and, thereby, sharing the total utility (8) bilaterally. That is, since the client does not bring any added value to the game, neither should he gain from the game 'for free'.

However, if the client requires that he is familiar with the manufacturing process, *e.g.*, to assure certain quality in the final product, he may accuse Suppliers 1 and 2 of breaking the contract when the trickery comes to light (the consequences of which depend on the contract, *etc.*).

This example motivates the following coalitional analysis. For each $i \in N_\upsilon, j \in N$, let $\tau_j(i)$ denote the utility (or cost) to player *j* if the contract between *i* and *n* is terminated. For convenience, we write $\tau_i(i) = \tau_i, \forall\ i \in N_\upsilon$. We assume that $\sum_{i \in N_\upsilon} \tau_i < 0$, that is there is always at least one supplier $i \in N_\upsilon$ such that $\tau_i < 0$. This assumption eliminates the possibility that all the suppliers ally against the client.

Let us define the *coalitional threat game* as a generalisation of the game (3) as follows:

$$v = (S \subseteq N,\ C_s, v(S)),$$

where *S* is a coalition, $C_S = \times_{i \in S} C_i$ is the set of strategies of the players in *S*, and $v(S)$ is a characteristic function. Originally, von Neumann and Morgenstern (1944) defined $v(S)$ by a *minimax* representation. We shall, however, use the definition presented by Harsanyi (1963). The idea is that, instead of maximising merely the total utility, a coalition should maximise the *difference between its own total utility and the competitors' total utility.* Thus, the coalitions' optimal strategies become:

$$c_S^* = \arg\max\nolimits_{c_S} \left(\sum\nolimits_{i \in S} \pi_i(c_S, c_{N \setminus S}^*) - \sum\nolimits_{j \in N \setminus S} \pi_j(c_S, c_{N \setminus S}^*) \right) \tag{17}$$

$$c_{N \setminus S}^* = \arg\min\nolimits_{c_{N \setminus S}} \left(\sum\nolimits_{i \in S} \pi_i(c_S^*, c_{N \setminus S}) - \sum\nolimits_{j \in N \setminus S} \pi_j(c_S^*, c_{N \setminus S}) \right). \tag{18}$$

The characteristic function is defined as:

$$v(S) = \sum_{i \in S} \pi_i(c_S^*, c_{N \setminus S}^*), \tag{19}$$

where the strategies $(c_S^*, c_{N \setminus S}^*)$ are obtained from (17) and (18).

4.3.2 Harsanyi's modified shapley value

An elegant means for finding an outcome for *n*-player bargaining is the Shapley value, which was introduced by Shapley (1953). The Shapley value for player *i* of a coalitional game *v* is:

$$\varphi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!(|N|-|S|-1)!}{|N|!}(v(S \cup \{i\}) - v(S)), \tag{20}$$

where $v(X)$ is the characteristic function (the worth) of coalition *X*. As has been discussed earlier, the possibility to use threats is an essential part of the game. For this purpose, Harsanyi (1963) presents a *modified Shapley value,* which is calculated from the original formula (20) but with the characteristic function defined in (17)–(19).

In our process-innovation game, the modified Shapley values for the suppliers $(1,..., n-1)$ and the client (n) are:

$$\varphi_i = \frac{\pi_{\max}}{|N_\upsilon|+1} - \frac{\tau_n(i)}{2} + \frac{\tau_i}{2}, \qquad i \in N_u \qquad \text{(a)}$$

$$\varphi_i = 0, \qquad\qquad\qquad\qquad j \in N_s \setminus N_\upsilon. \quad \text{(b)} \tag{21}$$

$$\varphi_n = \frac{\pi_{\max}}{|N_\upsilon|+1} + + \frac{\sum_{i \in N_\upsilon} \tau_n(i)}{2} - \frac{\sum_{i \in N_\upsilon} \tau_i}{2}. \qquad \text{(c)}$$

It is straightforward to verify that the players' modified Shapley values (21) sum up to the total available utility:

$$\sum_{i \in N_\upsilon} \varphi_i + \sum_{j \in N_s \setminus N_\upsilon} \varphi_j + \varphi_n = \pi_{\max},$$

that is, the allocation $\Phi = (\varphi_1 \ldots \varphi_n)$ is efficient.

The suppliers with $\tau_i < 0$ are in a weaker bargaining position than the other suppliers. We could say that the weak suppliers are more dependent on the client than the other suppliers. Thus, the modified Shapley value for the weak suppliers is strictly less than that for the other suppliers. In fact, the suppliers not dependent on the client obtain the same amount of utility that the egalitarian solution (12) would give, and the suppliers dependent on the client forfeit an amount of utility – proportional to the strength of the client's threat ($\tau_n(i)$, τ_i) – to the client.

The utility-sharing rule ϕ according to the modified Shapley value is obtained by replacing π_i in (1) by φ_i:

$$\phi_i = \Delta\upsilon_i + \frac{\pi_{\max}}{|N_\upsilon|+1} - \frac{\tau_n(i)}{2} + \frac{\tau_i}{2}, \quad \forall\, i \in N_s. \tag{22}$$

The rule (22) takes account of the fact that some of the suppliers are more dependent on the client (n) than the other suppliers. Hence, it is reasonable that the incentive for the former is lower than that for the latter.

5   Numerical application of innovation incentives

This section applies the results of Section 3 to a network that consists of two suppliers and a client (Figure 4). All the numerical values are fictitious. Let us denote the two suppliers by indices 1 and 2 and the client by index 3. The network manufactures a product, which is being sold to end customers by the client. The suppliers both have a vital role in the network, supplying the client with certain components of the final product, for which the client pays the suppliers a fixed payment per each component.

Figure 4   Enterprise network of the example
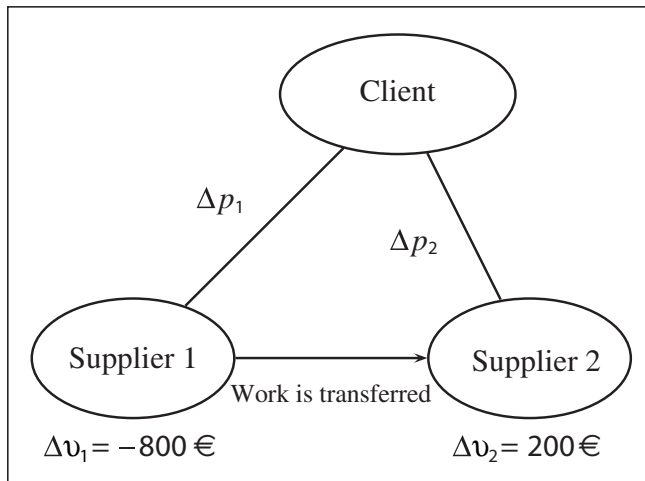
Among other duties, Supplier 1 carries out a job that, according to cost accounting, involves the expenses of 800 € per each final product manufactured. In negotiations within the network, it has become clear that Supplier 2 could perform the same job with costs of only 200 €. That is, by transferring the work from Supplier 1 to Supplier 2 the network could save up to 600 € per final product. This rationalisation manoeuvre, however, necessitates a change in the fixed payments (Δp_i's) that the client effects to the suppliers. By this simple example, we shall illustrate the calculation of the three different payment reallocations, which are suggested in Sections 4.1–4.3.

Following the notation introduced in Section 3, we have three companies $N = \{1,2,3\}$, and the set of suppliers involved in the process innovation is $N_\upsilon = \{1,2\}$. The changes in the suppliers' costs are:

$$\Delta\upsilon_1 = -800 \ \text{€}$$
$$\Delta\upsilon_2 = 200 \ \text{€},$$

and the total benefit of the work transfer is (from Equation (8)):

$$\pi_{\max} = -\sum_{i \in N_\upsilon} \Delta\upsilon_i = -(-800 + 200) \ \text{€} = 600 \ \text{€}.$$

It is noteworthy that, when no threats exist, in the determination of Δp_i's it is sufficient to know the values of $\Delta\upsilon_i$'s; no additional information is needed.

The relative threats solution enables the use of threats, *i.e.*, such actions that can harm a network company if committed by another company of the network. To illustrate how threats can affect the reallocation of the payments, let us assume that the client can terminate the contract with Supplier 1. Assume further, that the client can easily find a substitute supplier, whereas for Supplier 1 it is difficult to find a new customer. Hence, if the contract is terminated, the losses to Supplier 1 are valued at $\tau_1 = -150 \ \text{€}$, proportioned to the income of Supplier 1 from the present client. The client would not suffer any losses from the termination of the contract ($\tau_3(1) = 0 \ \text{€}$). Under these circumstances, the client possesses a credible threat against Supplier 1.

The egalitarian solution yields the reallocation calculated from the Equation (11):

$$\Delta p_1 = \Delta\upsilon_1 + \frac{1}{|N_\upsilon| + 1} \cdot \pi_{\max} = -800 \ \text{€} + \frac{1}{2+1} \cdot 600 \ \text{€} = -600 \ \text{€},$$

$$\Delta p_2 = \Delta\upsilon_2 + \frac{1}{|N_\upsilon| + 1} \cdot \pi_{\max} = 200 \ \text{€} + \frac{1}{2+1} \cdot 600 \ \text{€} = 400 \ \text{€}.$$

That is to say, Supplier 1, whose work load decreases, incurs a fall of $-600 \ \text{€}$ in the fixed payment from the client. Supplier 2, for one, receives a supplement of $400 \ \text{€}$ for the increased work load. The corresponding utilities, *i.e.*, changes in profit, become (by Equation (1)):

$$\pi_1^* = \Delta p_1 - \Delta\upsilon_1 = -600 \ \text{€} + 800 \ \text{€} = 200 \ \text{€},$$
$$\pi_2^* = \Delta p_2 - \Delta\upsilon_2 = 400 \ \text{€} - 200 \ \text{€} = 200 \ \text{€}.$$

The utility to the client is (by Equation (2)):

$$\pi_3^* = -\sum_{i \in N_\upsilon} \Delta p_i = -(-600 + 400) \ \text{€} = 200 \ \text{€},$$

Thereby, in the egalitarian solution, all the participants' utilities are equal, exactly as should be by (9).

The utilities according to *the relative threats solution* are calculated from the system of linear Equations (15)–(16), which in this example consists of three equations:

$$\text{(i)} \qquad \pi_1 - \tau_1 = \pi_2$$

$$\text{(ii)} \qquad \pi_2 = \pi_3 - \tau_3 (1)$$

$$\text{(iii)} \quad \pi_1 + \pi_2 + \pi_3 = \pi_{\max}$$

By solving Equations (i)–(iii) simultaneously, we obtain $\pi_1^T = 100$ €, $\pi_2^T = 250$ € and $\pi_3^T = 250$ €. The changes in the payments to suppliers become (by Equation (1)):

$$\Delta p_1 = \pi_1^T + \Delta v_1 = -700 \text{ €,}$$

$$\Delta p_2 = \pi_2^T + \Delta v_2 = 450 \text{ €.}$$

That is, as a consequence of Supplier 1's dependence on the client, Supplier 1 loses 100 € in comparison with the egalitarian solution. The surplus 100 € is divided up evenly among the client and Supplier 2.

In determining the solution according to the *modified Shapley value,* we assume the same interdependencies inside the network as in the previous solution. That is, the client possesses a credible threat $\tau_1 = -150$ € against Supplier 1. The changes in the payments are calculated from Equation (22):

$$\Delta p_1 = \Delta v_1 + \frac{\pi_{\max}}{|N_v| + 1} - \frac{\tau_3(1)}{2} + \frac{\tau_1}{2}$$

$$= -800 \text{ €} + \frac{600 \text{ €}}{2 + 1} - \frac{0 \text{ €}}{2} - \frac{150 \text{ €}}{2} = -675 \text{ €,}$$

$$\Delta p_2 = \Delta v_2 + \frac{\pi_{\max}}{|N_v| + 1}$$

$$= 200 \text{ €} + \frac{600 \text{ €}}{2 + 1} = 400 \text{ €.}$$

With this reallocation of the payments, the utility is shared in the network as follows (by Equations (1) and (2)):

$$\pi_1^S = \Delta p_1 - \Delta v_1 = -675 \text{ €} + 800 \text{ €} = 125 \text{ €,}$$

$$\pi_2^S = \Delta p_2 - \Delta v_2 = 400 \text{ €} - 200 \text{ €} = 200 \text{ €,}$$

$$\pi_3^S = -\sum_{i \in N_v} \Delta p_i = -(-675 + 400) \text{ €} = 275 \text{ €.}$$

Table 1 compares the results of the three presented solution concepts. As can be seen, the egalitarian solution π^* yields an equal payoff of 200 € to each company of the network (recall that a company's utility is measured as the change in its profit). This is due to the fact that the egalitarian solution was constructed by defining that the players' utilities should be equal.

Table 1   Comparison of the different solution concepts

Company	π^* (€)	π^T (€)	π^S (€)
1	200	100	125
2	200	250	200
3	200	250	275

The relative threats solution π^T penalises Supplier 1 for his dependency in respect of the client. Thus, Supplier 1's utility in π^T diminishes from the egalitarian solution π^* according to his disagreement losses. Therefore, the released utility (100 €) is balanced between the client and Supplier 2, who would not come to any harm, had the contract of Supplier 1 been terminated.

Also the solution according to the modified Shapley value π^s takes the dependent situation of Supplier 1 into account. However, the only participant who benefits from the weakness of Supplier 1 is the one who has the potency to execute the threat, *i.e.*, the client. Again, compared to the egalitarian solution, Supplier 1 suffers a loss of utility (−75 €), which is transferred to the client in its entirety. The transferred utility is proportional to the strength of the client's threat, but it is smaller in amount than in the relative threats solution. Also the client is better off in π^s than in π^T, because the third party (Supplier 2) does not benefit from the client's threat against Supplier 1.

6 Discussion

This section discusses the three solution concepts introduced in Section 4. It is common to all the three utility-sharing rules that a process innovation leads to a win-win situation among the companies involved. When this is a well-known fact within the network (*e.g.*, contracted), then the networked companies have the incentive to suggest efficiency-improving ideas. The aim of such mechanisms is to make the network drive self-steeringly towards the global optimum.

The main characteristics of the three solution concepts are presented in Table 2. The *egalitarian solution,* referred to as π^*, reflects complete cooperation between the companies, seeing that the utility is shared equally among the parties involved. Hence, we suggest that π^* is to be used when there is trust between the firms, or when the network is willing to create trust. This could be the case with affiliated companies, for instance. Apart from this, the *relative threats solution* (π^T) takes into account the different bargaining powers of separate companies. This includes, *e.g.*, the level of dependence between firms: if the interdependencies are biased, then the less dependent firms have better bargaining positions than the other ones. Such biased interdependencies commonly occur, for instance, between supplier and client or between brand owner and retailer. In addition to π^T, the solution according to the *modified Shapley value* (π^s) takes into account the possible coalition formation. Consequently, π^s can be used, *e.g.*, if the network consists of several companies who compete against each other.

Table 2 Main characteristics of the utility-sharing rules

Solution concept	Principle for profit sharing	Note
Egalitarian (π^*)	$\dfrac{\pi_{\max}}{\lvert N_\upsilon \rvert + 1}$	Profit is shared equally
Nash's relative threats (π^T)	$\displaystyle\max_{\sum \pi_i \le \pi_{\max}} \prod_i (\pi_i - \tau_i)$	Profit is shared proportionally to disagreement outcome
Harsanyi's modified Shapley value (π^s)	$\dfrac{\pi_{\max}}{\lvert N_\upsilon \rvert + 1} - \dfrac{\tau_n(i)}{2} + \dfrac{\tau_i}{2}$	Profit is shared proportionally to disagreement outcome and to the added value each player provides

The requirement for the implementation of the incentive model is that the suppliers are familiar with the changes in their costs that arise due to the process innovation. Usually, companies have trouble-free access to such basic information. Hence, the availability of the information is not an obstacle to the execution of the utility sharing. However, what might hinder is that the suppliers need also share the information with a third party who determines the compensation payments. Whether this is possible depends on the internal relationships of the network, *i.e.*, whether the companies trust each other.

Nevertheless, we argue that sharing the information should not be an obstacle to improving conditions. First, the amount of cost information to be revealed is normally attached to a single operation that a network company performs among its other duties. That is, the information is only a piece of the total cost information of the company and, hence, is not likely to cause harm to the company in the hands of another firm. Second, the information need only be exposed to one agent, who is able to determine the new allocation of payments inside the network. The agent could be, for instance, the client of the network, an independent consultant, or even a computer program. It may be advantageous to use an outside consultant, since the suppliers may trust the consultant more than their client. Every which way, except for the agent who calculates the payment reallocation, an individual participant of the rationalisation process accesses only the information on his own costs. In consequence, there is no fundamental risk that confidential information leaks to a third party who would benefit from the information at the expense of the companies of the network. Hence, we may assume that the firms have no restrictions to share the necessary information.

The use of the model is manifold. First, it can be directly implemented as an *ex-ante* utility-sharing contract. In such use, the model serves as an incentive to the suppliers to innovate. Second, already the bare modelling of the company network results in better understanding of the prevailing conditions in the network. Hence, the utilisation of decision-making models should not be restricted to experts; it is an efficient tool for the partnership management as well. In our experience from the case study, the model is not too complex to be adopted by a person who has the capability to approach problems analytically. That is, the person does not need to have a mathematical background; a basic understanding of the key concepts will suffice. Third, the model can be utilised to show the suppliers the importance and effect of process innovations and availability of information within the network.

7   Summary and conclusion

In this paper, we have introduced a game theoretic model for the identification of process innovations in company networks. Often, when a process innovation is implemented, the costs of some network companies increase, whereas the costs of some other network companies decrease. The first criterion for the rationalisation is that the total amount of costs decreases. The other criterion is that each of the network companies are better off after the rationalisation has been carried out. That is, the companies whose costs increase need a compensation payment in order to accept the implementation of the rationalisation manoeuvre. By our model, we show that these criteria can be satisfied and that joint gains are achievable through rationalisation.

This paper considers three incentive mechanisms that guarantee the network companies a gain when the total efficiency of the network increases. The gains to the individual network companies are financed by the cost savings that the increase in efficiency yields. Having such a mechanism explicitly contracted gives the network companies an incentive to suggest and implement process innovations. The first incentive mechanism introduced shares the utility equally among the companies involved in the rationalisation. The second utility-sharing rule is based on Nash's bargaining solution, which accommodates the possible biased interdependencies inside the network (Nash, 1953). Additionally, the third rule, based on Harsanyi's modified Shapley value, takes into account the possible coalition formation among the network companies (Harsanyi, 1963). Since the three rules are analytically solvable, the principles of utility sharing can be implemented, for instance, as *ex-ante* contracts.

As a summary, the main contributions of this paper are as follows: First, we have constructed a game theoretic model that can be used to study process innovations in company networks. Second, we have designed explicit mechanisms that encourage suppliers to process innovations. Third, our approach takes into account the biased interdependencies inside company networks.

A target for further development could be to extend the model to contain uncertainties of cost changes and disagreement outcomes (*i.e.*, the different *types* of the players and the states of the world). Harsanyi (1967–1968) conceptualised games with incomplete information by introducing games in Bayesian form. Thereafter, the theory of Bayesian games has been developed to a sophisticated level by numerous researchers. Hence, the (mathematical) means for the analysis of games with uncertainties exist. In general, the network management needs advanced models that support the objective of moving towards the global optimum.

Acknowledgements

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