Management Coordination for Multi-Participant Supply Chains Under Uncertainty

Kefah Hjaila, José M. Laínez-Aguirre, Luis Puigjaner and Antonio Espuña

Abstract A game decision support tool is developed to suggest the best conditions for the coordination contract between different stakeholders with conflictive objectives in a multi-participant Supply Chain (SC). On the base of dynamic games, the interaction between the involved stakeholders is modeled as a non-cooperative non-zero-sum Stackelberg's game under the leading role of one of the partners. The leader designs the first game move (price offered) based on its optimal conditions and taking into consideration the uncertain conditions of the follower. Consequently, the follower responds by designing the second move (quantity offered at this price) based on its best current/uncertain conditions, until the Stackelbergs payoff matrix is built. The expected follower payoffs are obtained taking into consideration the risks associated with the uncertain nature of the 3rd party suppliers. Results are verified on a case study consisting of different providers SC around a client SC in a global decentralized scenario. The results show improvements in the current/expected individual profits in the SCs of both leader and follower when compared with their standalone cases.

K. Hjaila (✉) · L. Puigjaner · A. Espuña
ETSEIB, Chemical Engineering Department, Universitat Politécnica de Catalunya,
Av. Diagonal 647, 08028 Barcelona, Spain
e-mail: kefah.hjaila@upc.edu

L. Puigjaner
e-mail: Luis.Puigjaner@upc.edu

A. Espuña
e-mail: antonio.espuna@upc.edu

J.M. Laínez-Aguirre
Department of Industrial and Systems Engineering, University at Buffalo, Buffalo, NY, USA
e-mail: jmlainez@gmail.com

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1 Introduction

Current tools for supporting SC planning decisions are based on the optimization of an overall target by assuming a centralized organization. Such approach disregards the complexity that may arise when considering the different objectives, possibly conflicting, of the different involved stakeholders, since in reality, each one usually seeks to optimize its own profits with no consideration of the uncertain reaction of the other players.

Some works have been carried out to solve these conflicting objectives through cooperative negotiations such as [1], who propose a cooperative multi-agent approach for the optimization of a Brazilian oil global SC. The objective in this work is to reach to an agreement to identify the oil products distribution plan. Zhao et al. [6] develop a bi-directional option contract (call option/put option) for a one manufacturer-one retailer decentralized SC. For the call option contracts, the manufacturer must buy a specific amount of products with a specific price, while for the put option, the retailer has to pay an allowance for cancelling or returning an order.

On the other hand, few works have been carried out to solve the conflicting objectives based on non-cooperative games. The work of [5] solve the interaction between different suppliers/retailers and one manufacturer through game theory. The competitiveness among the suppliers/retailers has been modeled as cooperative games through Nash Equilibrium (NE), while the interactions between the manufacturer and the suppliers/retailers have been modeled as non-cooperative Stackelberg games. Hjaila et al. [2] develop a scenario based dynamic-negotiation (SBDN) approach to solve the conflicts among the participating independent stakeholders within a decentralized SC. The authors consider the uncertain reaction of the followers SC as a probability of acceptance.

To the best of our knowledge, most of the decentralized SCs optimization models, based on either cooperative or non-cooperative games, focus on SC structures, where the interactions among the different stakeholders is hardly analyzed, leading to lose some practicality. Moreover, current methods based on game theory allow to provide individual decisions based on static cases, without considering the whole SC picture and how the other partners may react, thus giving a powerful position to one player (leader provider or client). This may lead to a bias representation of the decision-making process, particularly when the game players are subjected to risks due to the uncertainty in the expected response of their 3rd parties.

Accordingly, this work aims to suggest the optimal conditions for the coordination between different stakeholders, with different interests, within a decentralized SC superstructure. To illustrate the practicality of the proposed game approach, the developed models are implemented and solved for a superstructure of a manufacturing-distribution SC case study which is based on real data parameters. The decisions to be optimized are the resource flows and transfer prices between the participating SC stakeholders, production, inventory, and distribution levels.

2 Problem Statement

The Multi-Participant SC superstructure under study consists of several interacting manufacturing-distribution SCs (Providers and Clients SCs). The main players are the Provider and the Client, while the other stakeholders involved are considered as 3rd parties. The provider SC produces internal products which may be of interest to the Client SC and/or final products to external markets using resources from 3rd parties, so the Provider has the option to sell the same internal product to external markets, and the client can purchase the internal product from 3rd parties, giving more flexibility to both parties.

Based on dynamic (perfect information) games, in which each player information, strategies, 3rd parties, uncertain conditions, and benefits are known to each player, the interaction between the Provider and the Client is modeled as a non-cooperative non-zero-sum Stackelberg game under the leading role of the Client. The game takes into consideration the expected individual benefits of the Provider (Follower). The game items are the quantity and the transfer price of the internal product along the discrete planning time horizon. The reaction function of the follower is identified to be the quantity of the internal product at each planning time period.

Each player acts to optimize its individual benefits by taking into account that the other player is following the same goal. The leader player designs the game first move by offering the transfer price based on the available information, then the follower player reacts by providing the quantity. This is repeated until the Stackelberg payoff matrix is built, considering the follower current and uncertain conditions.

3 Mathematical Model

A set of SCs (*sc1*, *sc2* ... SC) is considered to represent the game with their new subsets linking each SC to its game player (leader L or follower F). The game items are the inner product $\acute{r}$ flows (RG) and the transfer price (p). The objective function is to maximize the SC Payoff (Eq. 1),

$$Payoff_{sc} = SALE_{sc} - COST_{sc} \qquad \forall sc \in SC \tag{1}$$

The SC revenue (*SALE*) (Eq. 2) is the summation of the sales to external markets m and to the leader SC (L); rp is the final product price, t is the discrete time period (*t1*, *t2* ... T), RD is the final product flow each time period, r is the final product resource.

$$SALE_{sc} = \sum_{r \in R} \sum_{m \in M} \sum_{t \in T} rp_{r,sc}.RD_{r,sc,m,t} + \sum_{r' \in R} \sum_{t \in T} p_{r'}.RG_{r',sc' \in F,t} \quad \forall sc \in SC, sc' \in SC \tag{2}$$

The SC Cost is the summation of the external resources purchase, production, storage, distribution, and the internal product costs, respectively (Eq. 3). Here, it can be seen the conflicting objectives, as the game term is considered as a sale in the follower SC model (Eq. 2), while as a cost in the leader SC model (Eq. 3).

$$COST_{sc} = CRM_{sc} + CPR_{sc} + CST_{sc} + CTR_{sc} + \sum_{r' \in R} \sum_{t \in T} p_{r'}.RG_{r',sc' \in L,t} \quad \forall sc \in SC, sc' \in SC \tag{3}$$

Managing uncertainty
The expected payoff (Eq. 4) of the follower is obtained using a Monte Carlo Simulation method. A sample consisting of N risk scenarios is generated.

$$ExPayof_{sc'} = \sum_{n \in N} \frac{Payoff_{sc',n}}{N} \qquad \forall sc' \in F \tag{4}$$

The mathematical model formulations result in Mixed Integer Non-Linear Programms (MINLP), for both leader and follower models. The complexity of the generic model stems from considering the policies of the third parties as part of the system. This is achieved by following the piecewise pricing model proposed by [3].

4 Results and Discussion

4.1 Case Study

The proposed approach has been implemented to solve a case study modified from [3]. The decentralized SC network (Fig. 1) consists of two main stakeholders: a polystyrene manufacturing-distribution SC stakeholder (leader) and an energy generation SC stakeholder (follower). The leader SC consists of 3 polystyrene manufacturing plants, 2 distribution centers (DC1, DC2), 3 markets (m1, m2, m3). The leader SC produces two products (A, B) using 4 raw materials (rm1, rm2, rm3, rm4) supplied from 4 vendors (sup1, sup2, sup3, sup4) and energy which is purchased from the local Grid. The follower SC consists of 6 renewable energy generation plants which are supplied by 4 biomass raw materials. The follower SC generates energy which is sold to final energy markets and the local Grid. The game is played to determine the optimal internal energy flows (economic/physical) between the follower and the leader SCs. To play the game, the leader offers energy prices (0.14–0.22/kWh), and consequentially, the follower responds by providing the internal energy amounts (3.0–24.71 GWh). The case study is modeled using the General Algebraic Modelling System (GAMS). The resulting MINLP tactical models are solved for 6 time periods, which consist of 1000 working hours each, using Global mixed-integer quadratic optimizer GloMIQO [4].

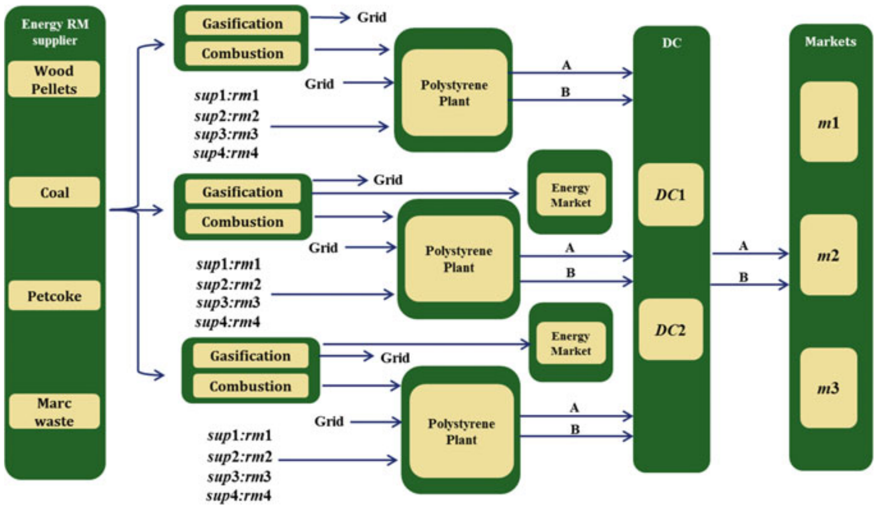

Fig. 1 The decentralized SC network [3]

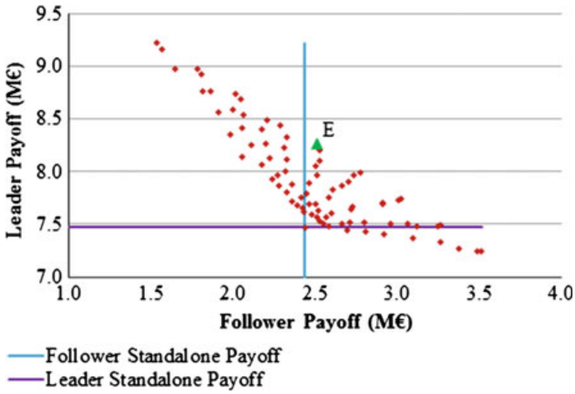

Fig. 2 Leader payoff versus Follower payoff

4.2 Results-Deterministic Conditions

The resulting Stackelberg's payoff matrix under the current energy prices around the follower SC has been projected on Fig. 2. It can be seen that the highest leader payoff value is 23 % higher than its Standalone payoff (7.47 M€), which corresponds to 59 % loss in the follower payoff compared with its Standalone payoff. The first win-win Stackelberg solution is the point E (Fig. 2), which guarantees 10.6 and 3 % profits improvements in the leader and follower payoffs, respectively in comparison with their corresponding standalone cases. Then, the resulting Stackelberg strategy would be to reach an agreement and signed a coordination contract that ensures a service of 24.71 GWh at a price of 0.18 €/kWh.

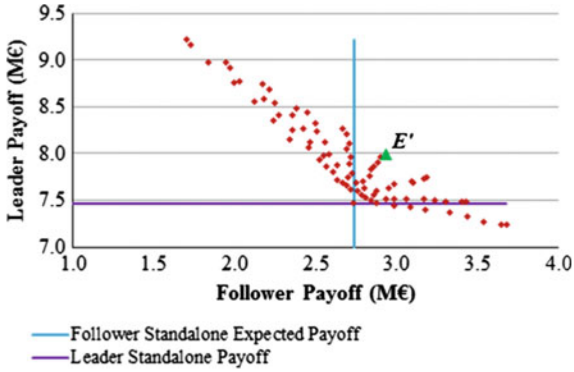

Fig. 3 Leader payoff versus Follower expected payoff

4.3 *Results—Uncertain Conditions*

The Stackelberg payoff matrix is built and projected on Fig. 3 based on the leader payoffs and the follower expected payoffs. This results are obtained from 500 generated scenarios using a Monte Carlo sampling based on the following parameters: energy prices mean = 0.22 €/kWh, standard deviation = 0.03 €/kWh. It is worth noticing that the Stackelberg solution has been shifted from E to É in order to mitigate the risks associated with the uncertain reaction of the follower. In this case, É represents the first win-expected-win solution. The coordination contract will be that one corresponding to the leader final strategy: 24.71 GWh at 0.19 €/kWh. Such a strategy results in 6.9 and 7.3 % profit improvements in the leader payoff and follower expected payoff, respectively in comparison with their Standalone cases.

Finally, the follower evaluates the game outcome based on its SC nominal expected payoff. To do so, the follower SC expected payoff (2.94 M€) according to the leader final strategy (É: 0.19 €/kWh) is compared with its expected nominal payoff at the leader strategy (E: 0.18 €/kWh). This is done by considering different 500 generated scenarios. The results show 6.6 % improvements in the follower expected payoff compared with its nominal expected payoff (2.76 M€).

5 Conclusions

A non-cooperative non-zero sum game approach is proposed for the optimization of decentralized SC. The methodological framework is based on determining the best coordination contract between the stakeholders of conflicting objectives (providers/clients) that guarantees win-win outcomes under the provider (the follower player) uncertain conditions. The Game approach results in different MINLP model implementations which have been solved to a real data case study that consists of different production-distribution providers SC (follower) around an industrial manufacturing-distribution SC (leader). The results show improvements in the stakeholders profit expectations when compared with their standalone situations. The uncertain behaviour of the follower affects the stackelberg outcome which induces the leader to change its strategy while keeping a win-win game outcome. The proposed approach provides a flexible decision-support tool that is able to mitigate the uncertain reaction of the providers, thus allowing to anticipate the mechanisms different manufacturers may use to modify their relationships with their providers during the decision-making process.

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