Production and transportation planning based on a cooperative game approach

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Abstract. This article is focused on the problem of planning coordination between manufacturer and transport operator inside a supply chain. A game theory approach is proposed in order to find a win-win planning solution. This approach is based on a cooperative game using the Shapley value in order to share profit between partners. This game uses linear programing models to simulate the supply chain planning activities. Through some preliminary results, we demonstrate that the profit of each partner can be increased.

Keywords: Production planning; Distribution planning; Cooperative planning; Game theory; Shapley value.

1 Introduction

Coordination is the management of dependencies between activities [1] and its purpose is to collectively achieve goals that individual actors cannot meet. As managing capabilities and resources across enterprise boundaries becomes increasingly important, coordination is considered as an essential issue to deal with performance improvement.

Coordinating production and transportation planning at the tactical decision level is a difficult problem, due to the different nature of partners involved in the decisional process and the dissimilarity of their profits margin – transport operators are known to make low profits in comparison with manufacturers.

The current article thus proposes to assimilate this problem to a cooperative game. In game theory, a cooperative game is a game where groups of players ("coalitions") may enforce cooperative behavior. For instance, this is the case when players choose the strategies by a consensus decision-making process.

In real world problems, many manufacturers and transport operators are involved in a same supply chain. Nevertheless, our work is limited to simplify coordination context, including one manufacturer and one transport operator. This situation, where the two partners share planning aggregated data without exchanging confidential detailed information, is an ideal support to lay the groundwork of coordination mechanisms, before extending them to a more complex supply chain.

This paper is organized as follows: section 2 presents a literature review. Section 3 describes the general problem in terms of partners involved in the study and also in terms of the cooperative planning method proposed. In section 4, our solving approach is defined: the cooperative game implementation is described. The experimental results are shown in section 5. Finally, in section 6, conclusion and some directions for future research are provided.

2 Literature review

The study of interactions between transportation and production activities in supply chains is not a recent concern. Many researchers have proposed centralized or decentralized solving approaches.

The coordination mechanisms between various partners of the supply chain were reviewed by [2]. Mula et al. [3] focuses on the specific relation between production and transport, and reviewed the mathematical programming models for supply chain planning. In addition to these reviews, other papers dedicated to this research topic are presented in the following. A whole supply chain in the pulp mill industry is considered in [4]; production and distribution planning problems are studied, and the authors use flexible ways to aggregate time periods to find good solutions within reasonable time limits. An integrated production and distribution planning on highly perishable products is studied in [5]. Through a multi-objective framework, the advantages of integrating these two intertwined planning problems in the integrated model at an operational level are explored. A solution approach based on the Lagrangian Relaxation approach of integrated model has been applied in a three echelons supply chain with multiple distribution centers [6], production sites and suppliers. A decentralized supply chain planning framework based on minimal-information sharing between the manufacturer and the third party logistics provider is proposed in [7].

Besides planning, another important topic in this article is game theory. Game theory can be used for decision making in the management of the supply chain activities. Some methods have been proposed in this field. The main types of games, their representations, and the main concepts used to analyze them are covered in the book [8]. Without claiming to be exhaustive, let us mention two main types of game: a non-cooperative game is one in which players make decisions independently; a game in which players can enforce contracts through third parties is a cooperative game. The problem of coordinating single manufacturer and multiple suppliers under demand uncertainty with asymmetric quality information is solved by a game theory model [9]. In [10], the authors propose to improve the tactical decision-making of a supply chain (SC) under an uncertain competition scenario through the use of different optimization criteria.

Let us mention the side-payment which is an interesting mechanism exploited in some studies field. It is defined as ‘‘an additional monetary transfer between supplier (buyer) and buyer (supplier) that is used as an incentive for deviating from the individual optimal policy” [11]. This concept is also used in two-persons, non-zero-sum supply chain games [12], as for instance a two retailers supply chain game with substitutable products and also in a one-supplier, one-retailer supply chain. The authors derive a proper side-payment scheme that can induce supply chain coordination and also solve the forward buying problem in a supply chain involving a supplier and a retailer.

The next section presents the problem definition and the general solving approach.

3 Problem definition and general solving approach

We assume that the two partners have their own independent decision making processes (Fig. 1). The only planning processes that are considered during the manufacturer decision making concern production and delivery activities, under constraints of finished products storage capacity and transport / production lead times. It is important to note that early and late deliveries can be authorized subject to the payment of a special fee (penalty), but are limited in number. The transportation planning process attempts to serve the manufacturer's delivery request as best as possible, while seeking to optimize the transport operator's profit. The limited number of owned vehicles and the possibility to use an extra capacity (outsourcing) are important parameters to be considered in the transport operator's decision making process. The same problem was studied by [13] who proposed a decentralized planning approach based on a dedicated negotiation protocol inspired from [14].

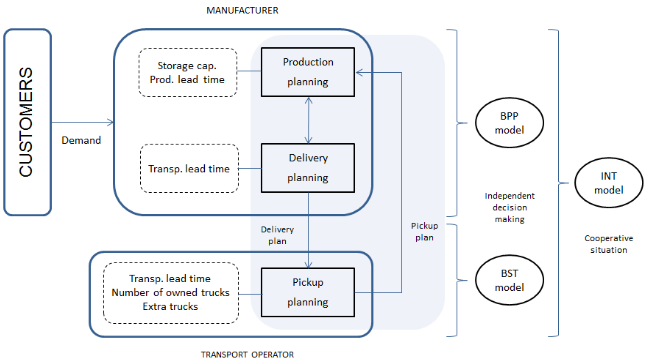

Fig. 1. Planning activities and linear models used to simulate decision making.

In this paper, game theory is chosen to solve a cooperative planning problem, which is oriented to the centralized planning. This choice is justified by the two following reasons: first, we aim to use a more generic negotiation principle based on theoretical foundation; secondly, we intend to reach a more balanced profit sharing between the transport operator and the producer than previously.

Among cooperative approaches, the Shapley value [8] was chosen because it provides a good mechanism to balance possible profit between partners who search efficient and fair solutions in order to collaborate.

In this game, manufacturer and transport operator are assimilated to players. These players can be organized in different groups (i.e. coalitions). The goal of the Shapley value is to find the best coalition dividing production and transportation profits in a satisfying way for each partner. The implementation of this game is given below.

4 Implementation of the cooperative game planning

4.1 Planning models overview

The Shapley value implementation requires estimating the payoff (i.e. profit) of all possible coalitions. For estimating the payoffs got by each partner, the planning decision making process of any coalition is simulated through the execution of a linear programming model.

In our study, only three coalitions have to be considered: the two simplified coalitions including only one partner (manufacturer or transport operator) which decides alone to make its own planning decisions; the coalition including the two partners together, which corresponds to the cooperative situation.

We consider thus three models represented in Fig. 1:

The "Best Profit Production" model, named BPP, corresponds to the coalition including the manufacturer alone who tries to maximize its profit regardless of any possible cooperation.

The "Best Service Transportation" model, named BST, allows assessing the financial gain that the transport operator can expect when its planning objective consists in seeking to respect as close as possible the delivery plan sent by the manufacturer.

The "INTegrated" model, named INT, which is represented in Fig. 2, encompasses in a single model all constraints and objectives of both the manufacturer and transport operator; this model is an efficient way to estimate the global gain when the manufacturer and the transport operator decide to work cooperatively. Through this model, delivery plan, production plan, inventory plan, and vehicles utilization plan are estimated.

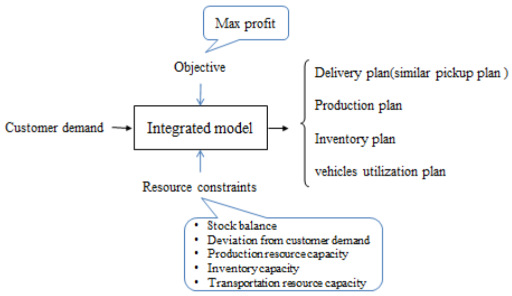

Fig. 2. The INTegrated model.

4.2 Single stage game using the Shapley value

Fig. 3 depicts the various plans (i.e. set of values of a planning decision variable for each time bucket of the planning horizon) generated by each model. It shows the difference between the generation of private data or plans (in dotted lines) that each partner does not wish to communicate and the generation of public data (in full form) that a partner accepts to share with others.

The BPP model simulates the manufacturer's independent planning processes, and BST simulates the transport operator's. BPP is run first and calculates the expected profit $P_I(BPP)$, and then BST is run to obtain the profit $P_I(BST)$. $P_M(INT)$ and $P_T(INT)$ respectively represent the profit of manufacturer and transport operator resulting from model INT, and $P_G(INT)$ represents the total profit of the coalition made up of the two partners.

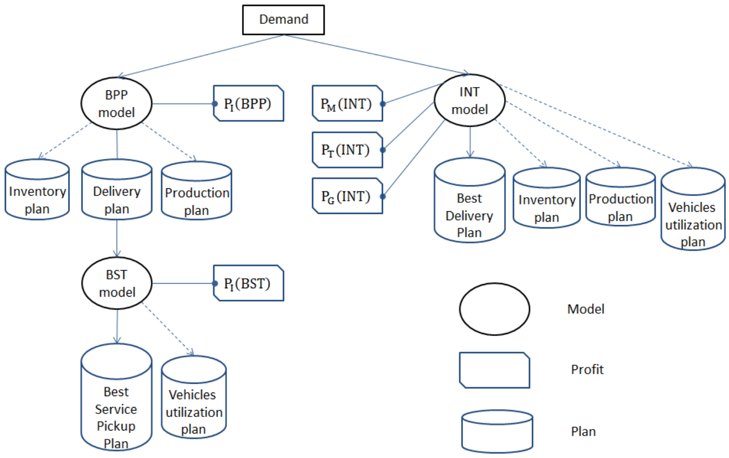

Fig. 3. Overall process of the profits calculation involved in the game

$P_I(BPP)$ and $P_I(BST)$ must be compared with $P_G(INT)$ resulting from the cooperation between the two partners, so that to define if the cooperative situation is interesting or not. This comparison is carried out through the following "Surplus" calculation:

$$\text{Surplus} = P_G(INT) - (P_I(BPP) + P_I(BST)) \qquad (1)$$

In case of positive surplus, the cooperation is considered as financially interesting but provides inventory, production and delivery plans with possible significant changes regarding those independently calculated by each partner. In case of success of cooperation, plans provided by the INT models are those applied to organize the manufacturer and transport operator's activities. In order to tackle this difference between plans, let us consider the main characteristics of the implemented solution.

The best targeted profits of the manufacturer and the transport operator are respectively given by the Shapley value ϕ_M and ϕ_T. The detailed calculation of Shapley values can be found in [8].

Notice that this estimation only re-introduces in the objective function the two following component: (1) The transportation fees paid from the manufacturer to the transport operator; (2) And penalties that the transport operator must pay to the manufacturer when decision to make early and late deliveries is due to transportation capacity limitation. These two elements explicitly considered in the objective functions of the BPP and BST models, are canceled when these functions are combined to build the objective function of the INT model.

The profit sharing, according to values calculated by the Shapley value, is based on a side-payment principle from a partner to the others. This side-payment is made in the following way:

If $P_M(INT) > \phi_M$, the manufacturer shall pay an amount of $P_M(INT) - \phi_M$ to the transport operator.

Conversely, the manufacturer shall receive an amount of $P_T(INT) - \phi_T$ from the transport operator.

5 Experiment results

An experimental platform has been developed, using the solver GLPK in order to implement all the planning models. In this experiment, the planning horizon equals to a month (22 working days) and the planning decision is made for each day.

5.1 Experiment input data

This test problem is made up of 22 time periods. In these experiments, there are two products, and each product can be delivered to two customers. Fig. 4 exhibits the profile of entire demand of product 1 and 2 in each period (i.e. whole planning horizon).

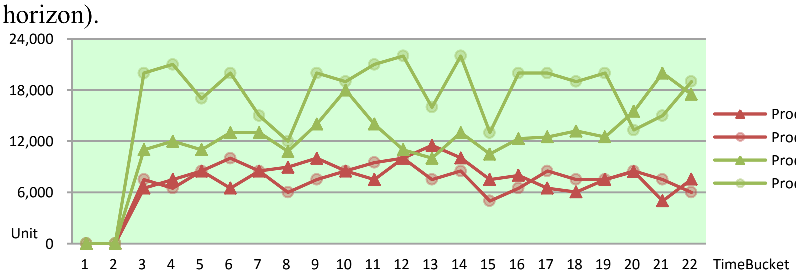

Fig. 4. Customers' demand

There are two main parts of the input parameters (i.e. data) corresponding to the two partners involved in the cooperation. Concerning production, the data concentrate on the demand, production capacity, production cost, inventory cost, selling price, and penalty price. About transportation, the parameters are related to the vehicles, the roundtrip time (i.e. the transport operator from the start to the depot picking up the products, then going to the customer and return), and finally the cost and price. The transport operator preferentially use own resources (i.e. vehicles) and when they are not enough to serve the production, extra resources will be employed. Due to the limitation of space, the entire input data are not be presented in this paper.

5.2 Results

The number of transportation owned trucks is chosen as input factor (i.e. parameter) in the experiments because it expresses the capacity of the transportation. Six experiments are carried out according to the number of transportation owned trucks. $P_I(BPP)$, $P_I(BST)$ and $P_G(INT)$ are calculated for each possible value of the input parameter.

The overall results show that production and transportation's profits grow from the independent case to the cooperative case. In order to better analyze this profit growth, we represent the profit growth rates of production and transportation R_M and R_T in Fig. 5, which are respectively calculated as shown in Eq. 2. These profit growth rates are consequently defined as ratios of improvement from the independent case ($P_I(BPP)$ respectively $P_I(BST)$) to the cooperative case (ϕ_M respectively ϕ_T).

$$R_M = \frac{\phi_M - P_I(BPP)}{P_I(BPP)}, \quad R_T = \frac{\phi_T - P_I(BST)}{P_I(BST)}. \tag{2}$$

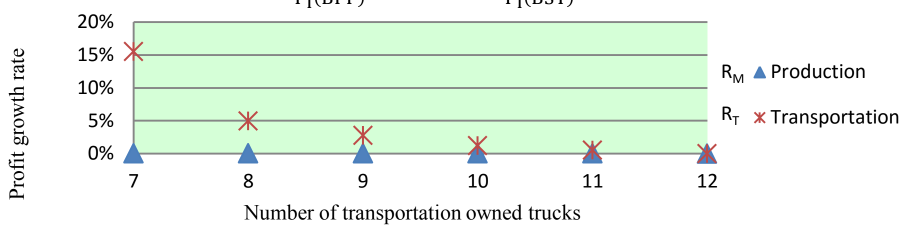

Fig. 5. Profit growth rate from the independent to the cooperative case

The following conclusion can be drawn: when the number of owned trucks increases, the profit growth rate of the transport operator decreases. Hence it can be concluded that cooperation is more meaningful when the transportation's capacity is not enough to serve the production pickup demand. Concerning the production, the profit growth rate is near zero, since the surplus is tiny compared with production's profit.

6 Conclusion

In this article, we intend to propose a new approach based on cooperative game and Shapley value concepts to solve the problem of low efficiency caused by a multiple stages negotiation protocol applied in decentralized planning models. Through the proposed preliminary experiments, some conclusions could be drawn: first, by using cooperative game, every partner-manufacturer and transport operator can get more profit, in a more balanced way; second, using of the Shapley value to divide the surplus profit is carried out in only one step compared with multi-steps negotiation in decentralized planning models [13].

Future development of this work will concern the following points. The fourth–party logistics (4PL) provider will be integrated as an explicit partner of the cooperation scheme between the manufacturer and the transport operator. The number of transport operators will be increased in order to tackle more realistic situations, since the power of Shapley value is not sufficiently revealed. In order to efficiently use the notion of coalition and Shapley value, and to really consider this approach as a generic one, an important extension will be the consideration of more than two partners in the game.

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