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Dynamic mutual adjustment search for supply chain operations planning co-ordination

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Operational planning is an activity carried out by all manufacturing and logistical companies. Its co-ordination with supply chain partners aims at synchronising resources utilisation in order to minimise inefficiencies, such as unnecessary inventory holding, or in order to improve revenue through better resource utilisation. It is a rather complex process as partners have different objectives and information asymmetry is part of any effort to find good co-ordination solutions. Furthermore, because supply chains evolve in a dynamic and uncertain environment, once a co-ordination of operations plans is achieved, input data, such as forecasts or resources' status, can change and affect on hand plans. These dynamic changes not only require updating the plan that is directly affected by the changes, but it also requires the adjustment of all plans that are part of the same co-ordination solution (Stadtler, H. 2009. A framework for collaborative planning and state-of-the-art. *OR Spectrum*, 31 (1), 5–30). Therefore, the development of a practical co-ordination approach should be capable of dealing with these dynamic changes. This paper proposes a dynamic mutual adjustment search heuristic, which can be used to co-ordinate the operations plans of two independent supply chain partners, linked by material and non-strategic information flows. Computational analysis shows that the proposed approach produces a win-win strategy in the context of two supply chain partners, and improves the results of upstream planning in each planning cycle, and also improves the fairness of revenue sharing when compared to optimal centralised planning.

Keywords: supply chain management; co-ordination; mutual adjustment search; rolling horizon planning

1. Introduction

Supply chains are distributed networks of interacting companies in a dynamic environment, which have to plan their operations in order to fulfil their commitments (e.g. the delivery of goods, the providing of a service) and achieve their performance objectives. The goal of supply chain management is the improvement of supply chain performance through the co-ordination of supply chain partners' resource utilisation in this dynamic environment. A more specific approach to achieving this goal is the co-ordination of operations planning activities in order to synchronise operations plans. Here, the concept of co-ordination space represents the set of all possible co-ordination solutions (i.e. vectors of operations plans of all considered supply chain partners) that satisfy the constraints of all partners.

The literature on supply chain operations planning co-ordination can be divided into two main streams of research: centralised vs. decentralised approaches. In centralised approaches, a central unit provides optimal plans for all supply chain members. Because they use a global view of supply chain operations, these approaches can theoretically produce an upper level of supply chain performance. In spite of performance optimisation, the implementation of centralised approaches requires a high degree of collaboration and information exchange among supply chain partners. Sometimes it is even necessary to share strategic information, like cost structures or bill of material, which could be used against partners to gain an undue advantage. Furthermore, centralised approaches of co-ordination are generally implemented through hierarchical relationships, which are only seen in large integrated supply chains. Therefore, centralised approaches of operations planning co-ordination are not practical solutions when supply chain partners are different companies that do not want share their critical information.

Opposite to central approaches, decentralised approaches are designed by explicitly considering the distributed nature of supply chains, in which each member is modelled as a separate decision-making entity with private strategic information. The simplest form of decentralised planning is upstream planning, or a one-way information

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flow (Azevedo *et al.* 2005, Dudek and Stadtler 2005), which can be considered as a weak form of hierarchy (Schneeweiss 2003). In fact, it is a cascade form of co-ordination in which partners independently plan their operations and send their own dependent demand to their suppliers. Because it is a rather simple form of co-ordination that is actually used in practice, upstream planning produces a lower bound of supply chain performance.

The research question addressed in this paper is how independent operations planning efforts can be co-ordinated in order to achieve near-optimal planning in a simple dyadic supply chain in a dynamic environment. Dynamic environments are characterised by continuously changing input data, such as updated forecasts or resource status, which has a ripple effect on partners because past decisions need to be updated. More specifically, we extend an approach first introduced in Taghipour and Frayret (2011b), and develop a mutual adjustment search (MAS) mechanism, in the form of a negotiation strategy, and evaluate the performance of this mechanism in a rolling horizon approach, in order to address the co-ordination of operations planning of a simple dyadic supply chain in a dynamic environment.

In brief, this mechanism involves two independent manufacturing companies, which interact with each other in a dynamic environment in order to improve their collective performance. Both companies plan their operations and decide, for each time period, what and how much to produce and deliver (i.e. multi-level capacitated lot-sizing problem). In the context of dynamic environment, input data, such as demand forecasts, are updated (between two planning cycle), and the output-input dependencies of both companies are updated using a mutual adjustment search, described in Section 3.2.

This approach requires only a minimum level of information sharing, because partners use financial incentives in order to influence their partner's planning, allowing them to deal simultaneously with material flows co-ordination and revenue sharing, unlike the pioneer approach of Dudek and Stadtler (2005, 2007).

Our objective is to develop and to demonstrate that MAS can improve supply chain co-ordination in a dynamic environment, compared with centralised planning and upstream planning. As discussed previously, these approaches are respectively used as upper and lower bounds in order to benchmark our approach. Computational tests show that MAS can co-ordinate supply chain partners, improve results of upstream planning, even produce near-optimal solutions in certain instances, as well as achieve a fairer sharing of increase revenue than central planning.

The remainder of this paper is organised as follow. A literature review is presented in Section 2. Then, Section 3 introduces the MAS approach. Section 4 present the experiments carried out to demonstrate the performance of the proposed approach in a dynamic context. Finally, Section 5 concludes and presents directions for future research.

2. Literature review

As mentioned in Section 1, centralised planning cannot be reasonably implemented as an efficient co-ordination of operations planning in supply chains with different companies. Indeed, it requires an unrealistic level of information exchange that is a deterrent to such a practice. In order to deal with these difficulties, the literature proposes many different paradigms of decentralised planning to address the co-ordination of independent partners.

Based on an analysis presented by Taghipour and Frayret (2011a), the literature that specifically deals with supply chain operations planning co-ordination can be classified into five main techniques and different sub-techniques. Following is a brief description of these co-ordination approaches.

2.1 *Exact decomposition and constraint-based techniques*

Based on mathematical decomposition techniques, these approaches decompose a large supply chain planning co-ordination problem into several distributed sub-problems, which are solved, generally by using some form of mediator, which acts as a co-ordinating agent that does not really make any decision, but rather support the other company agents co-ordinate their operations plans. Because these techniques are rooted in exact mathematical decomposition approaches, the co-ordination process involves generally an exact search within the co-ordination space, as well as exact local optimisations techniques. The adapted decomposition techniques are:

- Lagrange decomposition (Barbarosoglu and Özgür 1999, Ertogral and Wu 2000, Chen and Chu 2003).
- Bender's decomposition (Poundarikapuram and Veeramani 2004, Uster *et al.* 2007).
- Dantzig-Wolfe decomposition (Holmgren *et al.* 2009).

To this class of approaches, we also include a comprehensive distributed search with constraint propagation (Gaudrealt *et al*. 2009), which has theoretically the potential to identify the optimal solution. Although these are powerful mathematical tools to co-ordinate local decision processes, the main issue of their application concerns the difficulty to interpret the information exchanged between the sub- and the master problems by operations managers. Furthermore, only the last approach of 'distributed search with constraint propagation' is a method that has a weak dependency link between the co-ordination process and the local planning tools (i.e. which can be legacy advanced planning and scheduling systems-APS) and requires minimal information exchange.

2.2 *Hierarchical planning and information sharing techniques*

Initiated by Hax and Meal (1975), some authors propose to decompose the overall decision problem into a hierarchy problem and sub-problems linked by master–slave relationship in order to simplify the central complex problem into interdependent planning functions. Co-ordination is carried out in a cascade process from long term to short term decisions, or from customer to supplier. These approaches use some form of greedy/one-way information exchange to co-ordinate their input/output dependencies. This basic principle has been implemented in various co-ordination techniques, referred to as: greedy co-ordination; information sharing and anticipation model; and partial aggregation of decision domains. The simplest technique in this class of co-ordination approaches is 'greedy co-ordination', which consists of a simple one way exchange of information, also referred to as upstream planning (Bhatnagar *et al*. 1993). Partial aggregation of decision domains is a hybrid (Pibernik and Sucky 2007) co-ordination approach between centralised and upstream planning in order to fill the performance gap of upstream planning. Finally in the 'information sharing and anticipation' model, partners exchange more or less strategic information to co-ordinate one another. For instance, Váncza *et al*. (2008) proposes a mechanism in which one partner sends its non-strategic information, such as its demand forecast as well as its penalty mechanism, in order to improve the upstream planning approach. The main issue with the class of co-ordination approach is the absence of a systematic search of the co-ordination space.

2.3 *Heuristic search techniques*

In this class of techniques, partners progressively adjust their local initial plans through some form of local search procedures that involve iterative information exchange. Here, partners are capable of mutually adjusting their operations plans according to the constraints or capabilities of their partners. This form of co-ordination technique requires the design of a convergence mechanism to guarantee the improvement and the feasibility of the collective plan, as well as termination conditions in order to stop the incremental process of mutual adjustment. These techniques use a heuristic search (i.e. not an exact method) during the co-ordination process. Interaction mechanisms between supply chain partners can be either implicit (i.e. fixed and programmed) or explicitly formalised as an interchangeable interaction protocol that can be selected via an intelligent process (i.e. used by intelligent software agents). This class of approach can be divided into several sub-classes: distributed heuristic search with local optimisation (Dudek and Stadtler 2005, Jung and Jeong 2005, Taghipour and Frayret 2010, 2011b), meta-heuristic search (Silva *et al*. 2006) and interaction based co-ordination (Azevedo *et al*. 2005). Distributed heuristic search with local optimisation involves the exploration of the co-ordination space through iterative techniques between two partners that optimise their own operations plans with advanced planning and scheduling tools. Meta-heuristic searches propose to adapt meta-heuristics, such as ant colony optimisation, in order to develop local optimisation tools capable of exchanging specific information, such as pheromone matrix, to co-ordinate local operations planning. These approaches, however, are less practical because they tend to force supply chain partners to adopt highly specific meta-heuristic APS systems. Finally, interaction-based co-ordination approaches propose to formalise interaction protocols (e.g. finite state machine, UML, Petri nets) used within a fixed set of business rules by a reactive software agent. These approaches implement a heuristic form of specific information exchange tied with the use of specific local optimisation tools in order to carry out the operations planning co-ordination process.

2.4 *Intelligent and adaptive techniques*

Based on intelligent agent technology, this class of approaches exploits various advanced techniques of goal-driven planning and learning in order to develop software agents capable of adapting to their environments in order to choose the most appropriate action to perform and co-ordinate their planning decisions with other agents. In fact, in this class, instead of focusing on the interaction as the main mode of co-ordination (as in interaction-based co-ordination), the focus is put on the adaptive behaviour of the agents, which of course involves interacting with others. Because of this, such co-ordination approach can be referred to as adaptive heuristic co-ordination because the co-ordination process still remains heuristic. For instance, Cloutier *et al*. (2001) propose a 'commitment-based co-ordination approach', in which deliberative agents have the ability to commit to do certain task, and plan their own course of actions to plan their manufacturing and logistics operations in order to meet these commitments. Similarly, 'argument-based agent' involves the construction and exchange of arguments that agents believe will make their counterpart look more favourably upon their proposal (Jennings *et al*. 2001). Another form of adaptive technique are 'multi-behaviour agents' (Forget *et al*. 2008), which also have the ability to select their own course of actions, according to specific goals, to maximise a utility function or reach a goal. 'Learning-based agents' (Fox *et al*. 2000) can also adapt by progressively discovering, through machine learning techniques, the best course of action in specific situations.

2.5 *Bidding-based techniques*

Rooted in economics and market mechanisms, these techniques involve several forms of co-ordination techniques based on negotiation. The general form of co-ordination of operations between an initiating company and others is made through the selection of partner(s), whose offers are more efficiently co-ordinated with the initiating company. These approaches are often based on the Contract-net introduced in Davis and Smith (1983), which is intended for decentralised tasks allocation. In this technique, an initiator company sends a call-for-proposal to several potential partners and receives bids from them. Although bids are generally derived from one single planning alternative (Hu *et al*. 2001, Calosso *et al*. 2003, Ahn and Lee 2004), they can also contain several alternative sub-proposals to choose from, each one being derived from different local planning alternatives, as proposed in D'Amours *et al*. (1997). Another bidding technique that is also used is 'auction', as proposed by Lee and Kumara (2007), who developed a hierarchical auction structure of tasks allocation and co-ordination.

Based on the analysis of the literature presented by Taghipour and Frayret (2011a), out of almost 105 selected contributions to the supply chain planning co-ordination problem, less than 23% of these contributions consider the dynamic nature of supply chain co-ordination. This paper proposes to contribute to this gap by extending the approach introduced by Taghipour and Frayret (2011b) and introduce a 'distributed heuristic search with local optimisation' co-ordination technique, in which two partners iteratively explore the co-ordination space using a heuristic search algorithm based on financial incentives.

3. Problem statement and approach overview

The specific supply chain planning co-ordination problem addressed in this paper is a 'distributed multi-level capacitated lot-sizing problem' (d-MLCLSP) in a dynamic environment. In other words, two supply chain partners, bound by input/output constraints, must simultaneously solve their local MLCLSP, while co-ordinating their decisions with their supply chain partner, taking into account their local capacity constraints, which may be adjusted using overtime, and their local bills-of-material. The design of the co-ordination approach presented hereafter was driven by the need to not share any kind of strategic information, such as cost structures, capacity utilisation profiles and external demands. In this specific contribution, we also considered the need to develop a method that directly addresses the dynamic nature of supply chain co-ordination.

The proposed approach is called 'dynamic mutual adjustment search' (DMAS) and uses financial incentive. In fact, the use of an incentive system allows partners to iteratively explore a small set of alternative 'order plans' (OP), in order to improve the plans initially created through upstream planning.

An OP is the matrix of the manufacturer's order to the supplier for all products and all time periods of the planning horizon. In the proposed iterative co-ordination process, partners exchange a proposal in the form of alternative order plans and financial incentive, which must be evaluated by the partner in order to assess its

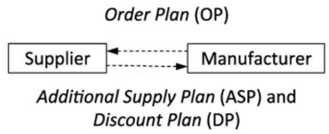

Figure 1. Exchanged information (Taghipour and Frayret 2011b).

feasibility and its impact on profit. In this mechanism, financial incentives are used by the supplier to incite the manufacturer to adjust its original OP, referred to as the upstream planning order plan.

In this mechanism, the supplier first identifies its optimal plan, in the neighbourhood of the plan derived from the manufacturer's original OP. The positive difference between these two plans (supplier optimal plan and plan derived from manufacturer's original plan) is referred to as the 'additional supply plan' (ASP) matrix, which represents the supplier's desire to increase the original order for specific products at specific time periods in order to improve its profit. Next, the supplier calculates the 'maximum discount' (MD) that can be offered to the manufacturer if he accepts in totality to co-ordinate his OP in accordance with the ASP of the supplier. The MD is defined as the gap between the profit generated from delivering its local optimal plan and the profit generated from delivering the manufacturer's original OP. Finally, using the ASP and the MD, the supplier defines and offers a 'discount plan' (DP) to the manufacturer, which consists in offering part of the MD for an adjustment of the original OP equal to part of the ASP. In other words, if the manufacturer decides to increase its original order plan for specific products at specific time periods up to at least the specified portion of the ASP, than a fixed discount is offered to the manufacturer. This incentive is radically different from typical quantity discount, which are proportional of the volume order. In this approach, the incentive is a fixed amount that is either given or not according to its impact on the manufacturer's profit.

These negotiation-like interactions are based on minimal level of information sharing (Figure 1). Unlike the pioneer approach proposed by Dudek and Stadtler (2005), which requires partners to exchange cost improvements along with the OP at each step of the negotiation process, the proposed approach proposes to use a dynamic discount structure that is progressively adjusted in order to find a compromise OP without sharing cost information. Furthermore, this approach addresses the co-ordination of both material and financial flows simultaneously.

3.1 *Calculation of maximum discount plan (MDP)*

As mentioned in the above section, after calculating the plan derived from manufacturer's proposed original OP (i.e. upstream plan) and identifying his optimal plan, in the neighbourhood of this proposed original OP, the supplier calculates the positive difference between these two plans, referred to as the ASP. The ASP represents the supplier's desire to increase the original order plan for specific products at specific time periods. In addition, the supplier calculates the MD, as the gap between the profits generated from these two plans.

In the next step, the ASP is normalised in the form of a weight matrix (in which the sum of all elements is equal to one and each element is less than or equal to one), in order to know how the MD should be split between all products and all time periods to focus the incentive towards the most significant elements of the gap between both lot-sizing plans.

Indeed, the weight matrix, which is referred to as the normalised ASP shows the degree of importance of each element of ASP, simply by dividing each element of ASP matrix by the sum of all rows and columns of this matrix. The rebate structure (plan) is calculated by distributing the MD to all product-period couples proportionally to the normalised ASP. This results in the definition of a MDP as shown in Figure 2.

The aim of this MDP is to generate a base in order to propose different DP to encourage manufacturer deviate from its original order plan.

3.2 *A negotiation strategy as a heuristic co-ordination search*

First, as proposed by Taghipour and Frayret (2011b), a mutual adjustment search can be used between two partners in order to mutually adjust their plans by exploring the co-ordination space and to improve the result of upstream planning, which is only optimal for the manufacturer. As explained in the previous sections, the supplier produces

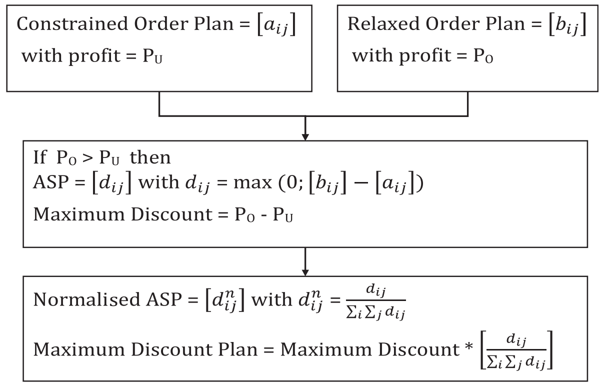

Figure 2. Generation of rebate plan by supplier (adapted from Taghipour and Frayret 2011b).

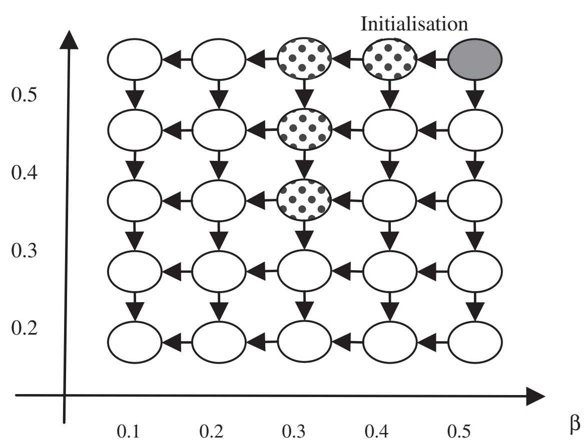

Figure 3. Mutual exploration of coordination space by couples of α and β.

and proposes iteratively different DPs derived from his MDP in order to incite the manufacturer to participate in the planning co-ordination action. The goal of proposing a discount is to compensate the manufacturer from any deviation of his optimal plan. In other words, the manufacturer can gain a DP, if he accepts to increase his original order plan for specific products at specific time periods up to at least the proposed specific portion of the ASP proposed by the supplier. More specifically, at every round of the mutual adjustment, α% of MDP, referred as DP (DP $= \alpha$ * MD, $0 \leq \alpha \leq 1$) is proposed to the manufacturer, if he accepts to increase his original OP up to β% of ASP (β * ASP, $0 \leq \beta \leq 1$). In this co-ordination approach, the co-ordination space that is potentially explored is therefore limited to any combination of α and β, which is a small subset of the actual co-ordination space. A simple example of exploring this co-ordination sub-space is presented in Figure 3. Here, the oriented arcs represent the potential moves from a DP proposal to another according to the heuristic proposed in this paper.

First, if the manufacturer refuses a given DP, the supplier simply reduces the deviation asked to receive the discount (i.e. β) until the manufacturer accepts the DP. At this point, the supplier must validate any adjustments made to the order plan by the manufacturer upon the receipt of this DP. If the supplier does not improve its initial profit with this new order plan, it decreases the discount (i.e. α) offered to the manufacturer without adjusting the deviation asked (i.e. β). This process is based on the hypothesis that the manufacturer trusts the supplier's will to improve the total profit of both partners. If there is no trust, for instance if the supplier only decreases the discount (i.e. α) in order to increase its own profit by simply taking advantage of the manufacturer, it is highly likely that over time, the negotiation will fail and the initial upstream planning solution will be used.

Figure 3 illustrates the proposed heuristic negotiation to improve the result of upstream planning. The supplier starts the adjustment by proposing a predefined couple α and β (for example $\alpha = 0.5$ and $\beta = 0.5$). Using these values, the manufacturer optimises its operations trying to take advantage of the DP. If the manufacturer accepts

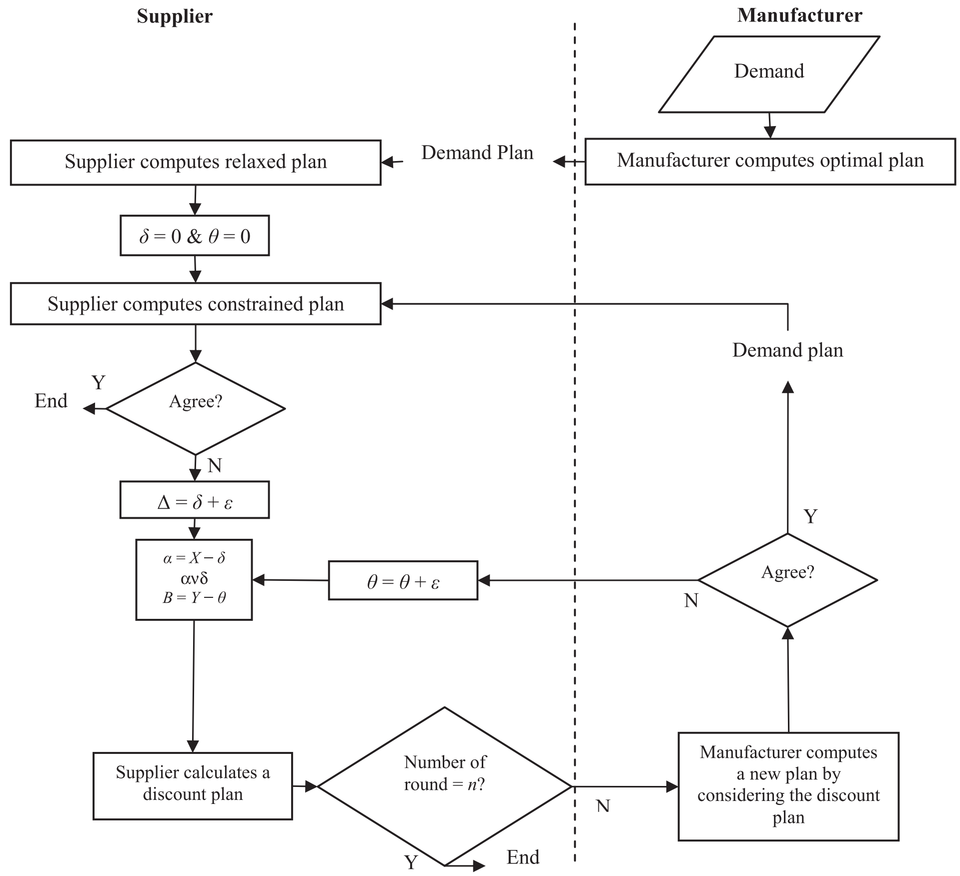

Figure 4. Mutual adjustment including a search algorithm to explore the co-ordination space by couples of α and β.

this discount plan, he sends a new order plan to the supplier. If he does not accept the DP, he does not change his original order plan. In this case, the supplier adjusts what he asked the manufacturer by decreasing the portion of ASP demanded with an inferior value for β (here, $\beta = 0.4$), but keeping the same discount (same α). This adjustment continues until the manufacturer accepts the discount and sends a new OP. At this point, the supplier evaluates whether or not this new OP increases his profit. If his profit does not increase its profit, then he does not accept the new OP and adjusts the discount by reducing the value of α (here, $\alpha = 0.4$). This process continues until both partners accept the DP and its associated new OP. If there is no agreement, then the upstream planning solution is the final solution. The mutual adjustment search can be terminated after certain number of iteration.

Figure 4 presents the complete mutual adjustment search (MAS), which includes the negotiation strategy described above. This heuristic approach can be summarised as follow.

Step 1: Manufacturer plans his operations

During the first stage, the manufacturer receives its external demand from his distributor and optimises his operations plan to maximise his profit, and sends his derived dependent OP (i.e. $Demandm_{f,t}$) to the supplier.

Step 2: Supplier optimises its operations with relaxed input/output constraints

When the supplier receives the manufacturer's original OP, he first computes a relaxed lot-sizing plan, which only considers an aggregated input/output constraint that consists in satisfying the total quantity ordered by the manufacturer over the planning horizon, and not the exact demand pattern.

Step 3: Supplier optimises its operations without relaxed input/output constraints

Next, the supplier calculates his upstream plan by considering the exact manufacturer's original OP (i.e. constraint based plan). This new plan leads to a second lot-sizing plan, which, in terms of profit, is, at best, equivalent to the relaxed plan.

Step 4: Supplier evaluation

If there is a significant difference of profits between these two plans (profit derived from relaxed plan-profit derived from upstream plan), the supplier calculates a DP in order to initiate the mutual adjustment process and incite the manufacturer to change his initial OP.

Step 5: Calculate discount plan

As explained previously, the supplier first calculates the ASP and the MD (i.e. the potential profit improvement) as illustrated in Figure 2. Next, the ASP is normalised in order to know how the MD should be split between all products and time periods in order to focus the incentive towards the most significant elements of the gap between both lot-sizing plans. Then, MD is multiplied by the normalised ASP. The result is the MDP. Next, using the heuristic negotiation strategy, at each round of the procedure, α percentage ($\in \alpha \in [0, 1]$) of the MDP (DP $= \alpha$ * MDP, $0 \leq \alpha \leq 1$) is offered for an increase of the manufacturer order plan equivalent to a β percentage ($\beta \in [0, 1]$) of the ASP.

Step 6: Manufacturer optimises his lot-sizes with new incentive

Next, the manufacturer computes the new lot-sizes taking into account the proposed DP sent by the supplier. If a new OP is computed, then it is sent to the supplier for evaluation in order to know the impact of this new OP and its associated discount plan on his profit. The supplier can then either accept this new OP or propose a more encouraging DP as discussed previously. Similarly, if the manufacturer does not change his original OP, the supplier can either accept it, returning to the initial upstream planning solution, or again propose a more encouraging DP.

The mutual adjustment can be terminated if both partners accept the discount and the new OP, or after a certain number of iterations, which implies that no solution has been found and that the original OP is the final solution.

3.3 *Mathematical models*

During the different steps presented in the previous section, mathematical models are used to optimise lot-sizes in specific situations. As mentioned previously, these planning models are multi-level capacitated lot-sizing models, inspired by Erengüc *et al*. (1999) and presented in Taghipour and Frayret (2011b). They are profit maximisation in order to address both material and financial flows co-ordination.

Model 1 (*Step* 1)*: First manufacturer optimal plan* (Z_1)

The first models correspond to Step 1 when the manufacturer first optimises his lot-sizes without considering any incentive.

Index sets

T Set of time periods.
J Set of products produced by the manufacturer.
$J_j^{\,s}$ Set of products directly succeeding product j in the bill of material (BOM).

Indices

t Time period, $t \in T$.
j Products produced by the manufacturer, $j \in J$.

Parameters

ps_f Unit price of product f produced by supplier.
$penalty_j$ Back order penalty for the manufacturer product j delivered to distributor.
$D_{j,t}$ Demand for product j in period t (produced by manufacturer).
$u_{j,g}$ Unit requirement of product j by successor operation/product g ($g \in j$).
pm_j Unit price of final product j produced by manufacturer.
cfm_j Fixed production setup cost of product j produced by manufacturer.
cvm_j Unit variable production cost for product j produced by manufacturer.
chm_j Unit holding cost for product j produced by manufacturer.
com_r Unit cost of overtime (capacity expansion) of resource r for manufacturer.
$cm_{r,j}$ Unit requirement of resource r to produce one unit of product j by manufacturer.

$Cm_{r,t}$ Production capacity of resource r in period t for manufacturer.
M A large number, which corresponds to the maximum quantity of product j that can be produced in a time period.

Variables

$dm_{j,t}$ Tentative delivery quantity of product j in period t to the distributor.
$om_{r,t}$ Overtime of resource r in period t for manufacturer.
$xm_{j,t}$ Output of operation/product j produced (or demanded from supplier) by manufacturer in period t (order plan).
$ym_{j,t}$ Setup binary variable for production of product j produced by manufacturer in period t.
$im_{j,t}$ Inventory level of product j in period t.
$bom_{j,t}$ Back order of product j produced in time t by manufacturer and delivered to distributor.

$$\text{Max}Z_1$$

$$\text{S.t.}:$$

$$Z_1 = \sum_{j\in J}\sum_{t\in T}\left(pm_j dm_{j,t} - cfm_j ym_{j,t} - cvm_j xm_{j,t} - chm_j im_{j,t} - ps_j xm_{j,t} - penalty_j bom_{j,t}\right) - \sum_{r\in R}\sum_{t\in T} Com_r om_{r,t} \tag{1.1}$$

$$im_{j,t-1} + xm_{j,t} = dm_{j,t} + \sum_{g\in J_j^s} u_{j,g} xm_{g,t} + im_{j,t} \quad \forall j \in J, \quad \forall t \in T \tag{1.2}$$

$$bom_{j,t} = bom_{j,t-1} - dm_{j,t} + D_{j,t} \quad \forall j \in J, \quad \forall t \in T \tag{1.3}$$

$$\sum_{j\in J} cm_{r,j} xm_{j,t} \le Cm_{r,t} + om_{r,t} \quad \forall j \in J, \quad \forall t \in T \tag{1.4}$$

$$xm_{j,t} \le M ym_{j,t} \quad \forall j \in J, \quad \forall t \in T \tag{1.5}$$

$$xm_{j,t} \ge 0 \quad \forall j \in J, \quad \forall t \in T \tag{1.6}$$

$$dm_{j,t} \ge 0 \quad \forall j \in J, \quad \forall t \in T \tag{1.7}$$

$$om_{j,t} \ge 0 \quad \forall j \in J, \quad \forall t \in T \tag{1.8}$$

$$im_{j,t} \ge 0 \quad \forall j \in J, \quad \forall t \in T \tag{1.9}$$

$$bom_{j,t} \ge 0 \quad \forall j \in J, \quad \forall t \in T \tag{1.10}$$

$$ym_{j,t} \in \{0,1\} \quad \forall j \in J, \quad \forall t \in T \tag{1.11}$$

The objective function (1.1) maximises the total profit of the manufacturer, which represents the profit incurred from the revenue generated by products sold minus the cost of production, inventory, purchasing, penalty for back order and capacity expansion through overtime. Constraint (1.2) captures the flow balance between, inventory, production, delivery and internal consummation of products for production. Next constraint (1.3) captures the back orders. Constraints (1.4) represent capacity restrictions. Constraints (1.5) to (1.11) specify domains of variable values.

Model 2 *and* 3 (*Steps* 2 *and* 3)*: Supplier relaxed and constrained plan* (Z_2 & $\overline{Z_2}$)

During Step 2, the supplier first computes its optimal relaxed lot-sizing plan, which consists in satisfying the total ordered quantity over the planning horizon.

Index sets

T	Set of planning periods.
F	Set of products managed by supplier.
F_f	^{s} Set of products directly succeeding product f in the BOM.
Fs	Set of product sold by the supplier to the manufacturer.

Indices

t	Planning period, $t \in T$.
f	Products produced by supplier, $f \in F$.

Parameters

ps_f	Unit price of product f in period t produced by supplier.
cfs_f	Fixed production setup cost of product f produced by supplier.
cvs_f	Unit variable cost for product f produced by supplier.
chs_f	Unit holding cost for product f held by supplier.
$De_{f,t}$	Demand for product f produced by supplier in period t from external customer.
$v_{f,g}$	Unit requirement of product f by successor operation g.
cos_r	Unit cost of overtime (capacity expansion) of resource r for supplier.
$cs_{r,f}$	Unit requirement of resource r to produce one unit of product f by supplier.
$Cs_{r,t}$	Production capacity of resource r in period t for supplier.
$Demandm_{f,t}$	Initial manufacturer order of product f in period t.
M	Large number.

Variables

$xs_{f,t}$	Output of product f produced by supplier in period t.
$ys_{f,t}$	Binary setup variable for production of product f by supplier in period t.
$is_{f,t}$	Inventory level of supplier product f in period t.
$ds_{f,t}$	Delivery quantity of product f in period t to manufacturer.
$de_{f,t}$	Delivery quantity of product f in period t to external manufacturer.
$os_{r,t}$	Overtime of resource r in period t for supplier.

$$\text{Max}\, Z_2$$

$$\text{s.t.: } Z_2 = \sum_{f\in F}\sum_{t\in T}\left(ps_f\left(de_{f,t}+ds_{f,t}\right) - cfs_f ys_{f,t} - cvs_f xs_{f,t} - chs_f is_{f,t}\right) - \sum_{r\in R}\sum_{t\in T} cos_r os_{r,t} \tag{2.1}$$

$$is_{f,t-1} + xs_{f,t} = de_{f,t} + ds_{f,t} + \sum_{g\in F_f^s} vs_{f,g} xs_{g,t} + is_{f,t} \quad \forall f\in F, \quad \forall t\in T \tag{2.2}$$

$$de_{f,t} \le De_{f,t} \quad \forall f\in Fs, \quad \forall t\in T \tag{2.3}$$

$$\sum_{t\in T} ds_{f,t} \le \sum_{t\in T} Demandm_{f,t} \quad \forall f\in Fs \tag{2.4}$$

$$\sum_{f=1}^{F} cs_{r,f} xs_{f,t} \le Cs_{r,t} + os_{r,t} \quad \forall f\in F, \quad \forall t\in T \tag{2.5}$$

$$xs_{f,t} \le M ys_{f,t} \quad \forall f\in F, \quad \forall t\in T \tag{2.6}$$

$$xs_{f,t} \geq 0 \quad \forall f \in F, \quad \forall t \in T \tag{2.7}$$

$$ds_{f,t} \geq 0 \quad \forall f \in Fs, \quad \forall t \in T \tag{2.8}$$

$$de_{f,t} \geq 0 \quad \forall f \in Fs, \quad \forall t \in T \tag{2.9}$$

$$os_{f,t} \geq 0 \quad \forall f \in F, \quad \forall t \in T \tag{2.10}$$

$$is_{f,t} \geq 0 \quad \forall f \in F, \quad \forall t \in T \tag{2.11}$$

$$ys_{f,t} \in \{0,1\} \quad \forall f \in F, \quad \forall t \in T \tag{2.12}$$

The objective function (2.1) maximises the supplier's profit, which represents the profit incurred from the revenue generated by sold products minus the cost of production, inventory, purchasing and capacity expansion through overtime. Constraint (2.2) captures the flow balance between inventory, production, delivery to the manufacturer, and internal consummation of products for production. Constraint (2.4) represents aggregated manufacturer demand satisfaction. Constraint (2.5) shows capacity restrictions. Constraints (2.6) through (2.12) specify domains of variable values.

Next in Step 3, the supplier computes its constrained lot-sizing plan. To do this, constraint (2.4) is replaced by constraint (2.4.1), while the same objective function is optimised (referred to as $\overline{Z_2}$ in this version of the model). Constraint (2.4.1) is used in order to satisfy exactly the manufacturer demand pattern.

$$ds_{f,t} = Demandm_{f,t} \quad \forall f \in Fs, \quad \forall t \in T \tag{2.4.1}$$

Once, both plans are computed, the supplier used Equations (3.5) to (3.7) to compute the discount structure of $Discount_{f,t}$.

$ASP_{f,t}$ Additional supply plan for product f at period t.

$$ASP_{f,t} = \max(0; ds_{f,t} - Demandm_{f,t}) \quad \forall f \in Fs, \quad \forall t \in T \tag{3.5}$$

$$\text{Maximum Discount} = Z_2^* - \overline{Z_2^*} \tag{5.6}$$

$$Discount_{f,t} = \left(ASP_{f,t} / \sum_{f \in F} \sum_{t \in T} ASP_{f,t} \right) * \text{Maximum Discount}$$

In brief, $Discount_{f,t}$ represents the maximum part of the discount that can be allocated to specific (product, periods) couples, in order to increase their 'attractiveness' to the manufacturers. Once this discount structure is calculated, the supplier proposes a percentage of the discount ($\alpha * Discount_{f,t}$ with $\alpha \in [0,1]$) if the manufacturer accept to increase specific part of its OP by a percentage of the ASP ($\beta * ASP_{f,t}$ with $\beta \in [0,1]$). This process can be repeated several times. At each round of negotiation the manufacturer receives a new DP in order to further improve the co-ordination. Once the manufacturer receives a DP, he optimises again its lot-sizes taking into account the DP. In order to do that, the objective function and several constraints are adjusted and added.

Model 4 (*Step* 6): *Manufacturer optimal plan with discount* (Z_3)

Parameters

$Demandm_{j,t}$	Initial order of products j in period t by manufacturer.
α	Percentage of a complete discount plan offered to manufacturer.
β	Percentage of a complete ASP plan demanded by supplier.
$ASP_{j,t}$	Additional supply plan proposed by supplier to manufacturer.
$Discount_{j,t}$	Maximum discount plan proposed by the supplier to the manufacturer.

Variables

$q_{j,t}$	Volume of product j ordered (without discount) in period t below the initial order plan.

Table 1. Upstream planning and supplier relaxed plan.

Upstream planning (supply chain profit = 1500)						Supplier relaxed optimal plan		
Manufacturer			Supplier			Supplier		
Profit = 1000			Upstream profit = 500			Optimal profit = 2000		
Product \ Period	1	2	Product \ Period	1	2	Product \ Period	1	2
1	20	0	1	20	0	1	0	20
2	10	0	2	10	0	2	0	10

$eq_{j,t}$ Volume of product j ordered (with discount) in period t above the initial order plan.
z *and* $w_{j,t}$ Binary variables used to enforce the discount structure.

Modified objective function

$$\text{Max } Z_3$$

$$\text{s.t. :}$$

$$Z_3 = \sum_{j\in J}\sum_{t\in T}\big(pm_j dm_{j,t} - cfm_j ym_{j,t} - cvm_j xm_{j,t} - chm_j im_{j,t} - penalty_j bom_{j,t} - ps_{j,t}q_{j,t} - (ps_{j,t}eq_{j,t} - \alpha * Discount_{j,t} * z)\big) - \sum_{r\in R}\sum_{t\in T} com_r om_{r,t}$$

New constraints

$$xm_{j,t} = q_{j,t} + eq_{j,t} \quad \forall j \in Js, \quad \forall t \in T \tag{4.2}$$

$$Demandm_{j,t} - q_{j,t} \le Mw_{j,t} \quad \forall j \in Js, \quad \forall t \in T \tag{4.3}$$

$$eq_{j,t} \le M_j(1 - w_{j,t}) \quad \forall j \in Js, \quad \forall t \in T \tag{4.4}$$

$$\sum_{t\in T}\big(eq_{j,t} + q_{j,t}\big) = \sum_{t\in T} Demandm_{j,t} \quad \forall j \in Js, \quad \forall t \in T \tag{4.5}$$

$$eq_{j,t} \ge \beta * ASP_{j,t}z \quad \forall j \in Js, \quad \forall t \in T \tag{4.6}$$

$$eq_{j,t} \le ASP_{j,t} \quad \forall j \in Js, \quad \forall t \in T \tag{4.7}$$

The objective function is similar to (1.1) except that it includes the discount. Binary variable z, together with constraint (4.6), is used in order to make sure that the discount is offered if and only if the manufacturer makes all increases of order quantity demanded by the supplier. In other words, if for a couple (product, period) the manufacturer does not respect the order increase corresponding to $\beta * ASP_{j,t}$, then the discount is not given.

Constraints (4.2) to (4.4) are used to calculate the part of the new OP that is above the original OP. Constraint (4.5) is used to limit the overall quantity of products ordered by the manufacturer to the level previously ordered. Similarly, thanks to constraint (4.7), the manufacturer cannot increase these quantities more than the ASP calculated by the supplier, as the impact of such increases on the supplier's profit would be difficult to anticipate. If the new resulted OP is different from the original OP, then it is sent to the supplier to be evaluated. The supplier can then either accept this new OP, or propose a new discount if the maximum number of round has not been reached. In this case, Step 4 does not have to be repeated.

3.4 *Illustration example*

In order to illustrate the complete approach, an example is presented in Tables 1–3. This example considers a supply chain that produces two products over two planning periods. Table 1 shows the result of upstream planning as well

Table 2. Supplier rebate calculation.

Supplier maximum discount plan calculation								
ASP matrix			Normalised ASP ($ASP_{f,t}/\sum_{f\in F}\sum_{t\in T} ASP\ f, t$)			Maximum discount plan (contributing the maximum discount ($2000-500=1500$) to normalised ASP)		
Product \ Period	1	2	Product \ Period	1	2	Product \ Period	1	2
1	0	20	1	0	20/30	1	0	1000
2	0	10	2	0	10/30	2	0	500

Table 3. Mutual adjustment.

Mutual adjustment								
First discount plan			First ASP plan			Manufacturer and supplier agreed plan		
$\alpha=0.5$			$\beta=0.50$			No agreement		
Product \ Period	1	2	Product \ Period	1	2			
1	0	500	1	0	10			
2	0	250	2	0	5			
Second discount plan			Second ASP plan			Manufacturer and supplier agreed plan		
$\alpha=0.5$			$\beta=0.40$			Supply chain profit = 2200 (Manufacturer = 1200, Supplier = 1000)		
Product \ Period	1	2	Product \ Period	1	2	Product \ Period	1	2
1	0	500	1	0	8	1	12	8
2	0	250	2	0	4	2	6	4

as supplier relaxed plan. If the supplier accepts the initial OP of the manufacturer, the supply chain total profit is 1500 monetary units (the manufacturer gains 1000 and the supplier gains 500 monetary units). The supplier then computes a relaxed optimal plan (with potential profit of 2000 monetary units) and finds a significant profit gap between the constrained plan (upstream planning) and the relaxed optimal plan ($2000-500=1500$). This profit gap (potential gain) indicates the maximum discount that can be proposed to the manufacturer.

In Table 2, in order to propose a discount plan to the manufacturer, the supplier calculates the normalised ASP and the resulting maximum discount plan matrix.

Table 3 shows the mutual adjustment process. In order to incite the manufacturer to participate in the co-ordination process, a couple ($\alpha * MaximumDiscountPlan_{j,t}, \beta * ASP_{j,t}$), which in this example are based on the value $\alpha=50$ % and $\beta=50\%$, is proposed to the manufacturer. The value of α is concealed from the manufacturer. In this example, the first proposed discount plan is not high enough to incite the manufacturer to modify his original order plan. Therefore, the supplier adjusts the couple ($\alpha * MaximumDiscountPlan_{j,t}$, $\beta * ASP_{j,t}$) to incite the manufacturer a little more. In the following table, the proposed ASP is adjusted by considering an inferior value for β ($50\%-10\%=40\%$), keeping the same rebate structure ($\alpha=50\%$). Therefore, in the second round, the co-ordination is achieved with an improvement of the supplier and the manufacturer profits (respectively $1000-500=500$ monetary units for the supplier, and $1200-1000=200$ monetary units for the manufacturer). Finally, because of a better utilisation of both their capacities, the result of upstream planning is improved for the entire supply chain ($2200-1500=700$ monetary units).

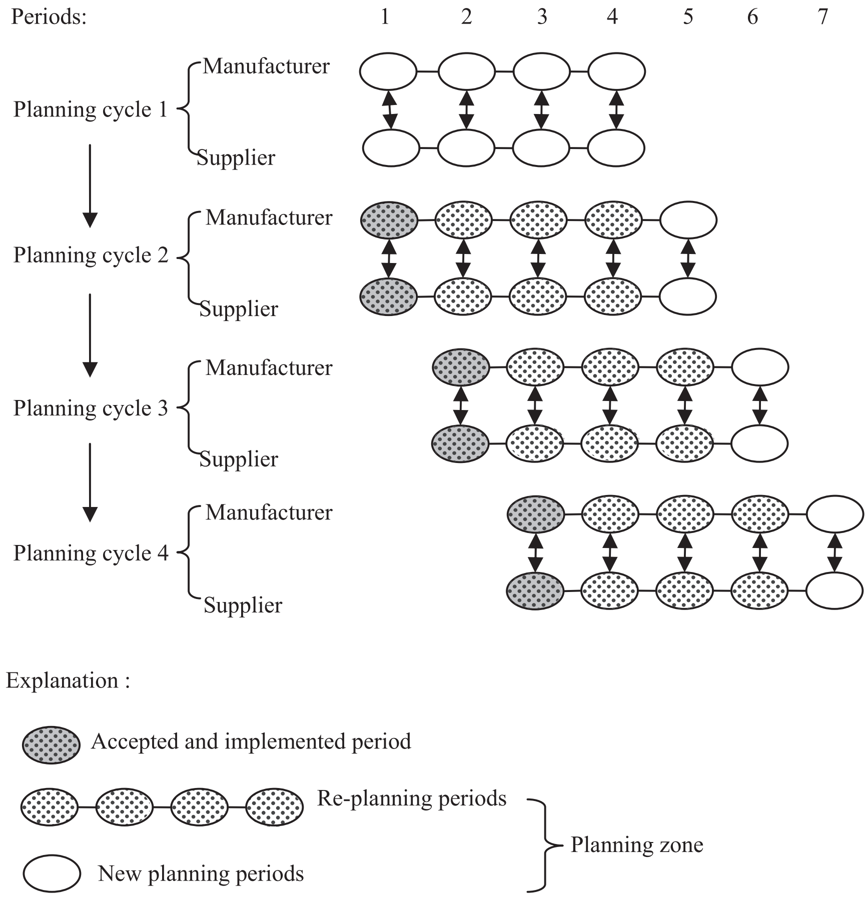

Figure 5. Mutual rolling horizons considered for test.

4. Application of mutual adjustment search in a dynamic environment

The heuristic approach of co-ordination described in the previous section addresses the supply chain planning co-ordination problem from a single planning cycle perspective, which is how most co-ordination approaches proposed in the literature address this problem (Taghipour and Frayret 2011a). However, in the real business environment, as time passes, decision parameters, such as demand forecasts, customer orders, and resources status are updated, which affects on hand plans and renders their co-ordination obsolete. In other words, these local dynamic changes require that all affected co-ordinated plans must be adjusted (Stadtler 2009), while part of the plans is implemented (i.e. first few periods). Furthermore, in the context of a co-ordination approach based on financial incentives that are distributed throughout the entire planning horizon, several issues must be resolved. These issues are first discussed in the next sub-section. Next, in order to adapt our general co-ordination approach to a dynamic environment, we first use a rolling planning horizon approach, within which we apply the mutual adjustment search (MAS). Then, we propose two revenue sharing protocols that enable partners to share their increased revenue gained from the implementation of the first period of the planning horizon.

4.1 *Issues*

In order to illustrate the issues involved in the development of a dynamic operations planning co-ordination approach, let's consider a rolling planning horizon that consists of four time periods, four planning cycles, and a planning cycle time of one time period, as shown in Figure 5.

At the beginning of each planning cycle, the manufacturer and the supplier mutually negotiate and adjust their operations plans for the four time periods (i.e. the entire planning horizon). However, although all planning periods are planned, only the planning decision of the first period is implemented at the next planning cycle. Here, we do not consider a frozen horizon, because it does not affect results and it does not add any particular difficulty in terms of implementation.

The first practical issue here is the fact that after the beginning of a planning cycle, demand information changes for all periods, including the three first time periods, which were already negotiated and planned in the previous planning cycle. Therefore, it is necessary that both partners update the non-implemented time periods (i.e. periods 2 to 4 of the previous planning cycle) by mutually readjusting their plans, subject to these changes. This implies that any given time period of the planning horizon is planned four times before it is implemented.

Furthermore, because only the first time period of the negotiated planning horizon is implemented, while all time periods are considered for the computation of the incentive, it is necessary to apply a revenue sharing protocol based on the proposed incentive structure in order to reward the contributions made by the manufacturer in the first time period to the general co-ordination problem (i.e. any positive or negative adjustments that contribute to achieving the desired order plan pattern).

Therefore, one contribution of this paper is to propose two revenue sharing protocols to address this issue. One of the objectives of the experiments proposed in Section 5 is to verify that these protocols do not affect the fairness of revenue sharing over time.

4.2 *Revenue sharing protocols for dynamic mutual adjustment search*

As mentioned in the previous section, it is necessary to develop and apply a profit sharing protocol for the first implemented period. In this paper we propose two protocols. In our first profit sharing protocol, we consider the discount derived from the first period of the DP and the contribution of this first implemented period to the adjustment of other periods of the plan, but limited by the supplier's ASP (Equation (5.1)). In our second protocol, we consider the relative contribution of the adjustments made in the first period with respect to the sum of all adjustments (i.e. for all periods) of the manufacturing's OP, regardless of their direct contribution to achieving the desired OP adjustment pattern (Equation (5.2)).

Parameters

Paiddiscount	Profit shared for the first implemented period of product j.
$ASP_{j,t}$	ASP for product j at period t
$a_{j,1}$	Contribution of the first implemented period of product j in the adjustment.
$d_{j,t}$	DP for the adjustment of product j at period t according to the ASP.

First revenue sharing protocol:

$$Paid\ discount = \sum_{j\in J}\left(\left(\sum_{t\in T} d_{j,t}\right) * \frac{\left[\mathrm{Min}\left(\sum_{t\in T} ASP_{j,t};\ |a_{j,1}|;\ \mathrm{Max}\left(ASP_{j,1};\ ASP_{j,1}-a_{j,1}\right)\right)\right]}{\sum_{t\in T} ASP_{j,t}}\right) \tag{5.1}$$

Second revenue sharing protocol:

$$Paid\ discount = \sum_{j\in J}\sum_{t\in T} d_{j,t} * \frac{|a_{j,1}|}{\sum_{t\in T}|a_{j,t}|} \tag{5.2}$$

In order to illustrate the impacts of these two protocols, we propose the two following examples.

In Table 4, according to our first protocol, the first period of the initial manufacturer's order plan contributes to an adjustment of 2 units of the second period and 4 units of the third period of the supplier's proposed order plan. Therefore, the paid discount for the first implemented period of manufacturer is 25 monetary units. When considering the second protocol, the relative contribution of the adjustments made in the first period is 50%. Consequently, the profit shared to the manufacturer is 50% of the sum of the discount plan for this product.

In Table 5, according the first protocol, the third period of the initial manufacturer's OP contributes to an adjustment of 10 units of the first period of the supplier's proposed OP. Therefore, the paid discount for the first implemented period of manufacturer is 20 monetary units. When using the second protocol, the relative

Table 4. Discount paid for the adjustment of this first implemented period (example 1).

Periods	1	2	3	4	Periods	1	2	3	4
Initial manufacturer's order plan	15	5	10	5	$ASP_{p,t}$	0	2	4	0
New order plan	7	7	14	7	Discount plan ($d_{p,t}$)	0	5	20	0
Adjustments ($a_{p,t}$)	−8	+2	+4	+2					
Paid discount (first protocol)	25								
Paid discount (second protocol)	12.5								

Table 5. Discount paid for the adjustment of this first implemented period (example 2).

Periods	1	2	3	4	Periods	1	2	3	4
Initial manufacturer's order plan	15	0	10	10	$ASP_{p,t}$	10	0	0	0
New order plan	25	0	0	10	Discount plan ($d_{p,t}$)	20	0	0	0
Adjustments ($a_{p,t}$)	10	0	−10	0					
Paid discount (first protocol)	20								
Paid discount (second protocol)	10								

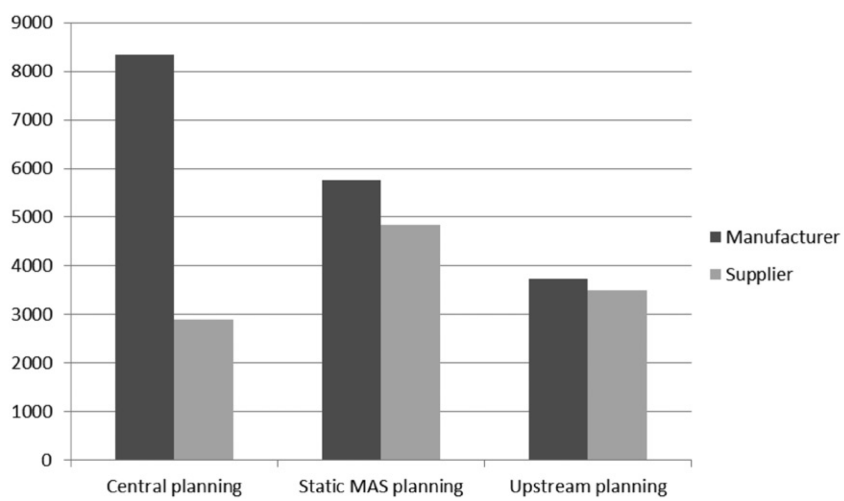

Figure 6. Average profit distribution comparison.

contribution of the first period is 50%, for a paid discount of 10 monetary units. These examples illustrate that the first protocol is more generous for the manufacturer than the second protocol.

5. Experimentations

In the context of a static environment application of MAS approach, Taghipour and Frayret (2011b) proposed a systematic analysis of the potential of such a co-ordination approach. To do this, we calculated the improvement of the initial OP for all possible combinations of α (0... 1) and β (0... 1) for several scenarios. The best combination for these scenarios showed that MAS has the potential to improve global supply chain profit (compared to upstream planning), as well as each partner's profit (Figure 6). In other words, the co-ordination of the partners' operations

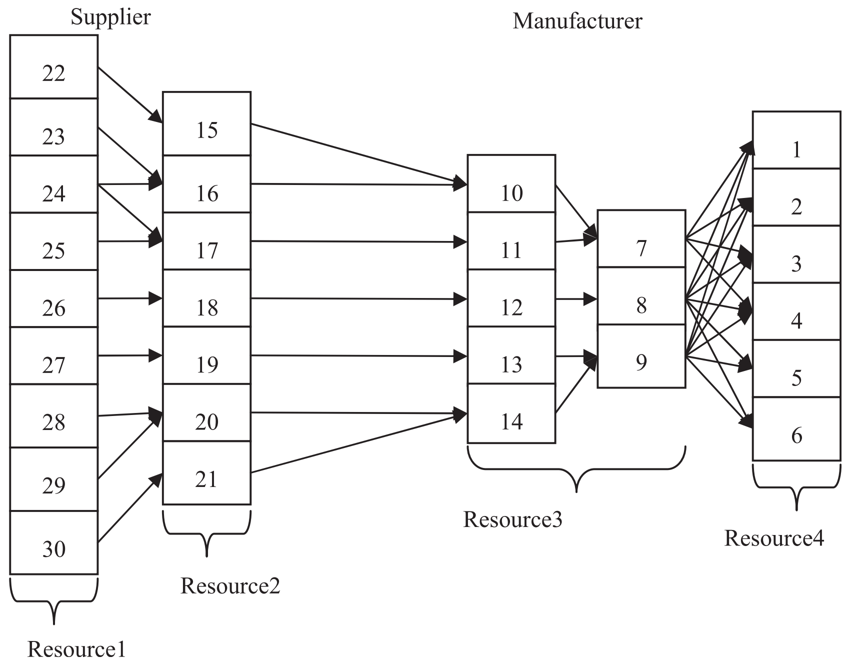

Figure 7. Complex test class for single supplier and manufacturer.

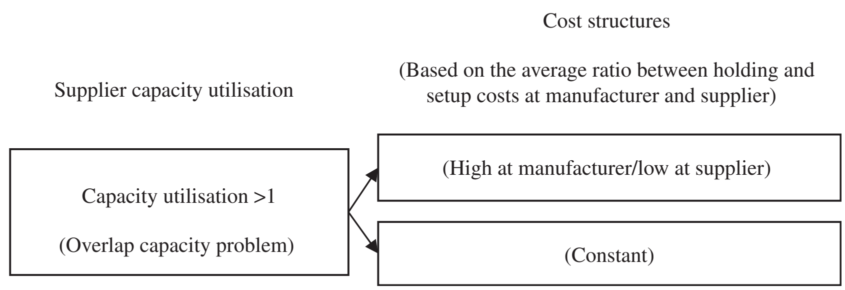

Figure 8. Instances of test.

(leading to increasing profit) and the fair sharing of these increased profits can be done simultaneously without any exchange of strategic information, contrary to other approaches like Dudek and Stadtler (2005 and 2007).

In this paper, and in order to assess the performance of this dynamic application of the MAS approach, a series of experiments have been conducted. The next section describes the experimental design and the results obtained.

5.1 *Experiment design and performance measures*

The objective of these experiments is to demonstrate that the proposed approach can lead to improved co-ordination compared to both upstream planning and centralised planning (in terms of profit improvement and revenue sharing fairness) in a dynamic environment. In order to analyse the dynamic implementation of the MAS approach and the revenue sharing protocols, a set of experiments were derived from a test class described in Figure 7. These tests include two partners, each of which possesses two manufacturing resources. The product structure considered has a five-level bill-of-material, which includes 30 products and components, produced by these two partners.

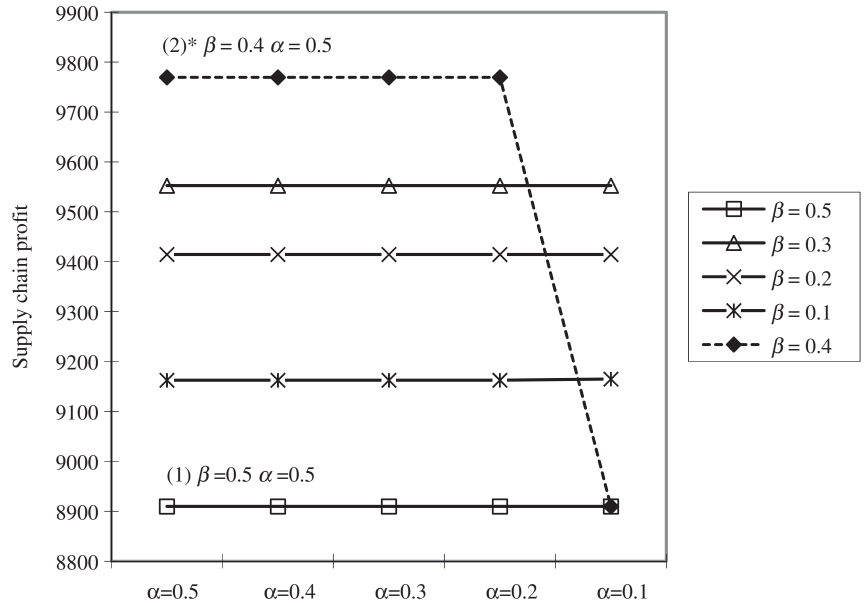

Figure 9. Potential supply chain profit improvement for scenario 1 – planning cycle 1.

The four mixed integer models presented in the previous section were implemented. Next, we derived two instances of test using this structure by combing one capacity utilisation profiles and two cost structures created based on average ratio between holding and setup costs at buyer and supplier (equal, high at manufacturer/low at supplier), as described in Figure 8. In addition, five values for α and β were considered ($\alpha = 0.1 \ldots 0.5$ and $\beta = 0.1 \ldots 0.5$) in order to evaluate further the performance of MAS across the entire planning horizon. Then, in each planning cycle a new set of demand parameters is used by considering demand forecast and customer order adjustments. These adjustments are drawn from normal distributions with zero mean and a standard deviation of 10% of average demand of each sold product. These combinations of scenarios result in [2 (two instances) * 5 (five values for α) * 5 (five values for β)] 50 computational experiments in each of the four planning cycles. Finally, the two proposed profit sharing protocols were also considered in order to compute the profits of both supply chain partners in the first implemented period of each planning cycle.

In order to benchmark the solutions of the MAS approach, we also computed two benchmark tests by calculating the profit of the first implemented period of each planning cycle for each partner according a lower bound solution (i.e. upstream planning) and an upper bound solution (i.e. centralised planning). ILOG OPL 6.3 and Cplex 10 mathematical programming solver were used to solve the optimisation models (taking almost one minute for solving each model). An overview of the test results is given in the next section.

5.2 *Computational results and analysis*

In order to evaluate the performance of the MAS approach, two analyses were considered. The first analysis deals with the performance of each planning cycle by considering the profit over the entire planning horizon, as in a static environment. This set of experiments is used to specifically evaluate the performance of the heuristic negotiation strategy proposed in this paper. The second set of experiments and analysis deals with the profit generated dynamically, in which only the performance of the first implemented period of each planning cycle is considered.

5.2.1 *Performance of MAS in a static environment*

Based on the results of the experiments described in Section 4.1, Figures 9–16 present the results for the entire planning horizon. Each figure includes the 25 co-ordination solutions investigated, which represent the total supply chain profit computed over all planning periods. In addition, the values (1) and (n)* respectively represent the start and the end of the MAS negotiation process in order to illustrate the improvement of quality of solution.

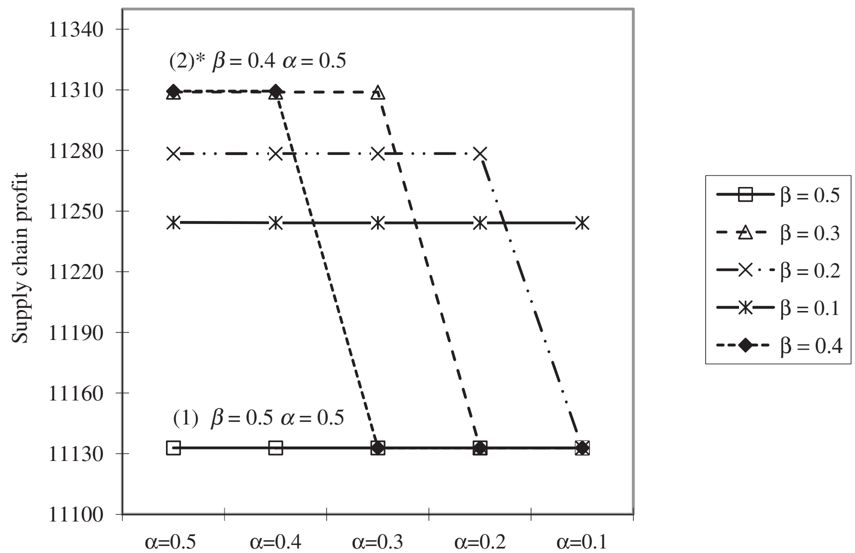

Figure 10. Potential supply chain profit improvement for scenario 1 – planning cycle 2.

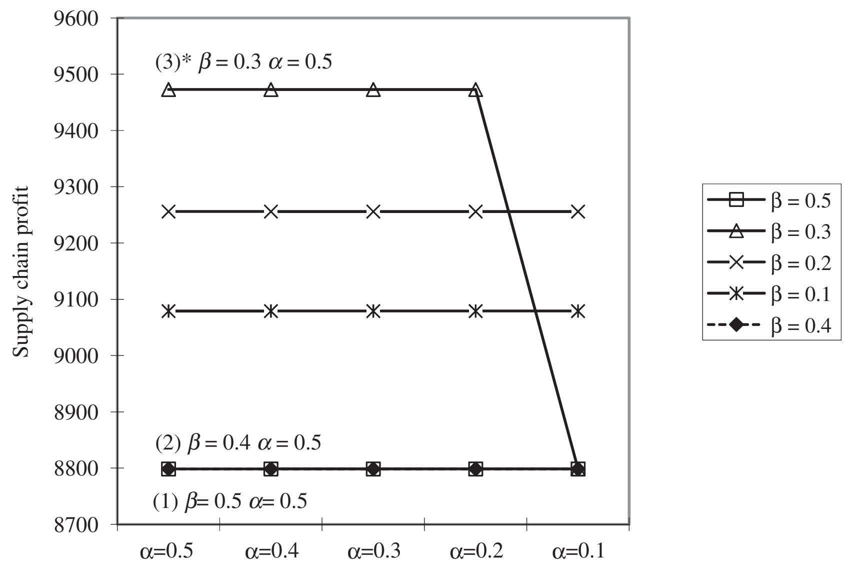

Figure 11. Potential supply chain profit improvement for scenario 2 – planning cycle 1.

In the first scenario, and considering only the first planning cycle, the MAS approach starts with the supplier's first proposal with a discount plan (i.e. numbered (1)) with $\alpha = 0.5$ and $\beta = 0.5$, as seen in Figure 9. Because there is non-agreement at this stage of the negotiation, the supplier proposes a new discount plan (i.e. numbered (2)*) with $\alpha = 0.5$ and $\beta = 0.4$. At this stage, an agreement is reached with a 9% improvement

$$\left(Supply\ chain\ improvement\ rate = \frac{MAS\ profit - Upstream\ profit}{MAS\ profit} \right)$$

over the upstream planning for the global supply chain.

For the second planning cycle of the first scenario, the negotiation starts identically (1) and an agreement is also reached for the supplier's second proposal (2)* with $\alpha = 0.5$ and $\beta = 0.4$. This agreement represents a 2% improvement in the results of upstream planning for the global supply chain.

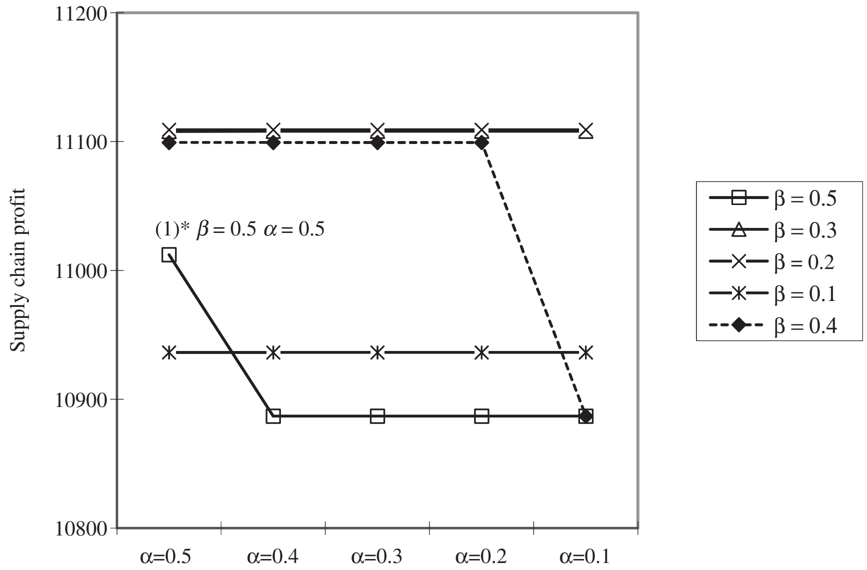

Figure 12. Potential supply chain profit improvement for scenario 2 – planning cycle 2.

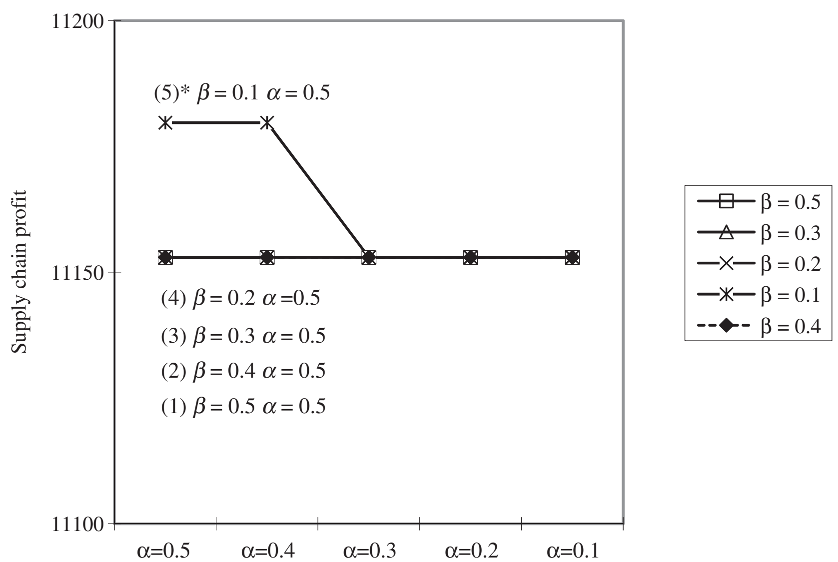

Figure 13. Potential supply chain profit improvement for scenario 2 – planning cycle 3.

For the third and fourth planning cycles of the first scenario, difference between the results of centralised planning and upstream planning is less than 0.4%. The MAS approach did not improve the initial solution; therefore, the upstream planning solution is used.

For the first planning cycle of the second scenario, after three rounds of negotiation (shown as (1), (2) and (3)*), an agreement is reached. The two first proposals of the supplier do not change the results of upstream planning, with respectively $\alpha = 0.5$ and $\beta = 0.5$, and $\alpha = 0.5$ and $\beta = 0.4$. However, with values of $\alpha = 0.5$ and $\beta = 0.3$, the supply chain profit improves by more than 7% the results of upstream planning for the global supply chain.

For the second planning cycle of the second scenario, the agreement is achieved with the first supplier's proposal with $\alpha = 0.5$ and $\beta = 0.5$, for a more than 1% improvement in the results of upstream planning for the global supply chain.

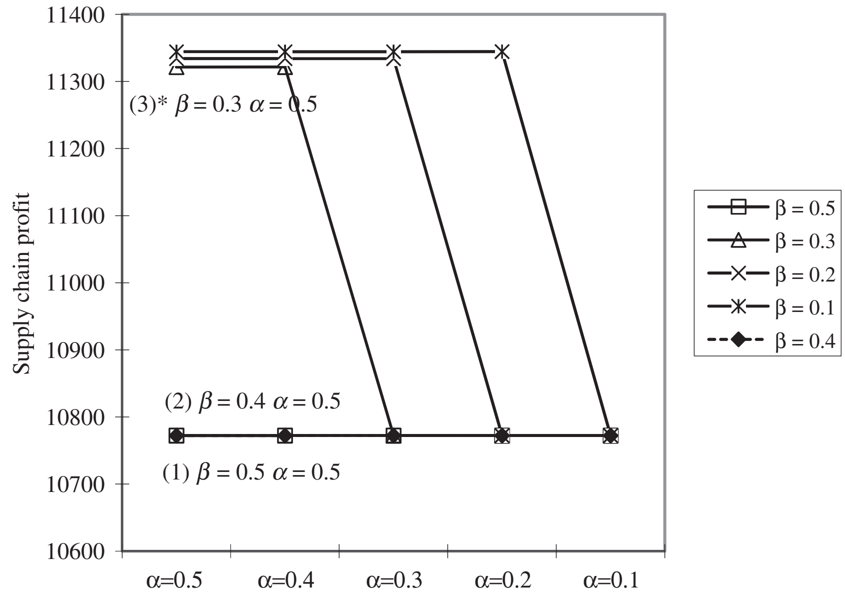

Figure 14. Potential supply chain profit improvement for scenario 2 – planning cycle 4.

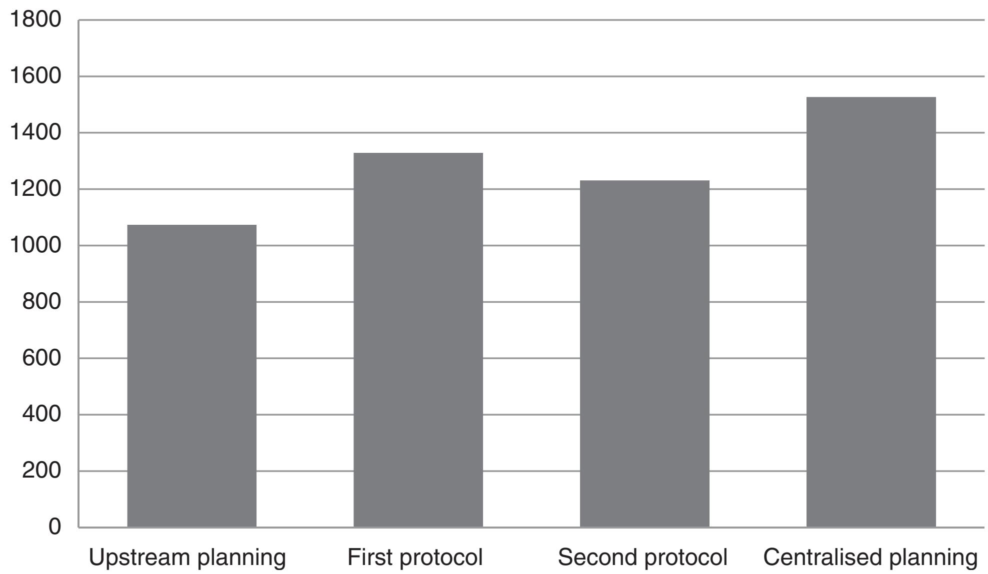

Figure 15. Manufacture's average shared profit for the implemented periods in scenario1.

For the third planning cycle of the second scenario, the agreement is achieved after five rounds of negotiation (shown as (1), (2), (3), (4) and (5)), with $\alpha = 0.5$ and $\beta = 0.1$, and a less than 0.3% improvement for the global supply chain.

Finally, for the fourth planning cycle of the second scenario, the agreement is achieved after three rounds of negotiation, with $\alpha = 0.5$ and $\beta = 0.3$, which represents less than 0.5% improvement.

The deviations between the best results of MAS approach and other approaches (centralised and upstream planning), visualised in Table 4, show that by using this MAS approach, partners can achieve a co-ordination pattern which improves profit of supply chain up near to the result of central planning.

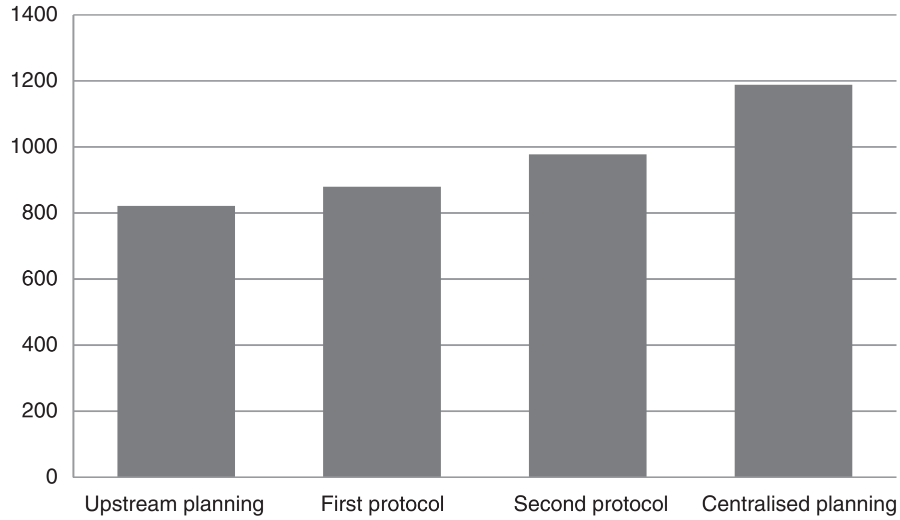

Figure 16. Supplier's average shared profit for the implemented periods in scenario 1.

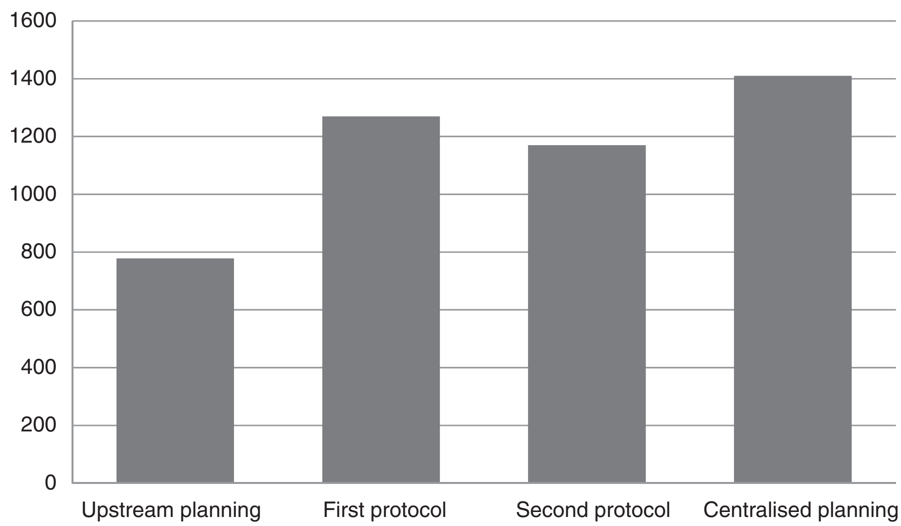

Figure 17. Manufacture's average shared profit for the implemented periods in scenario2.

5.2.2 *Performance of the dynamic MAS approach*

As mentioned previously, this section presents the results of a set of experiments designed to evaluate, on the one hand, the performance of the dynamic implementation of the MAS approach, which only concerns the first implemented periods of the entire planning horizon, and, on the other hand, the two revenue sharing protocols proposed in this paper. The results are compared to the equivalent solutions generated by the upstream planning and the central planning solutions reported in Figures 15–18.

As shown in these figures, the level of performance of the d-MAS approach depends on the selected profit sharing protocol. In these experiments, the fairness of the central planning approach is actually very good as both partners show an improved profit compared to upstream planning. Next, these experiments show that giving a higher degree of importance to the first implemented period in the calculation of the discount paid (i.e. first revenue sharing protocol) can generate an average of 19% profit increase for the manufacturer and less than 7% profit for the supplier compared to upstream planning in the first scenario. However, in the second scenario, the manufacturer experiences an average profit increase of almost 39% while the supplier experiences a loss compared

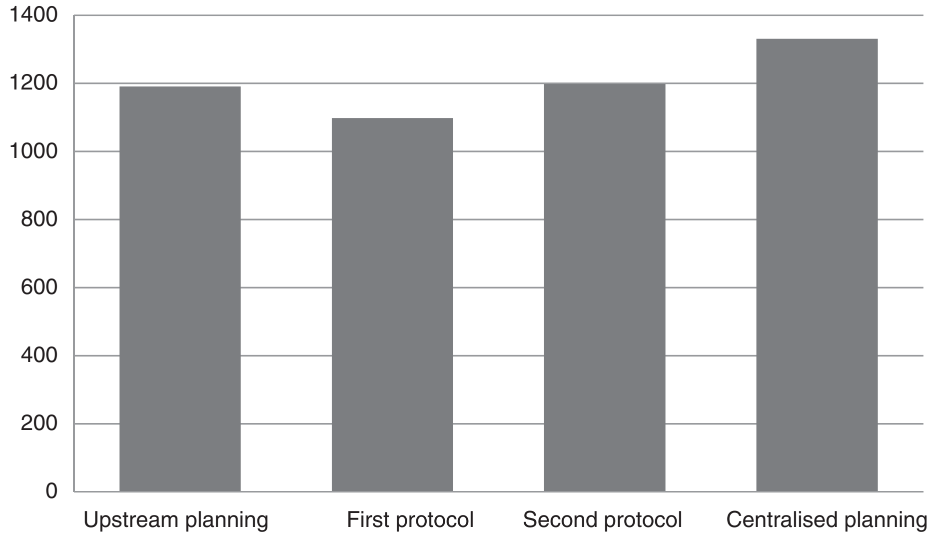

Figure 18. Supplier's average shared profit for the implemented periods in scenario 2.

to upstream planning. In the second scenario, the use of the second revenue sharing protocol within the d-MAS approach produces an average profit increase for both partners.

These experiments show empirical evidences supporting the fact that the use of the d-MAS approach in conjunction with the use of second revenue sharing protocol produces, on average, an improved profit for both partners. Similarly, these results also show that the first revenue sharing protocol can lead to unfair revenue sharing, and should therefore be avoided.

6. Conclusion

In order to co-ordinate supply chain partners in a dynamic environment, this paper proposed a dynamic mutual adjustment search (MAS) based on mathematical rolling horizon programming approach, to co-ordinate two partners of a supply chain in a dynamic environment. Our approach is a distributed decision making problems which gives the same decision authority to all partners without any exchange of strategic information. An incentive system is used to encourage partners to participate in the co-ordination process. Computational analysis shows that the proposed approach produces a win-win strategy for two partners of supply chain and improves the results of upstream planning in each cycle of planning.

The proposed MAS approach for bilateral co-ordination can be extended to the relationships of more than two partners in order to consider supply chain realistic condition. As another extension for the future research the re-negotiations of already accepted plans in a dynamic environment can be considered in order to improve the results of accepted plans.

References

Ahn, H.J. and Lee, H., 2004. An agent-based dynamic information network for supply chain management. *BT Technical Journal*, 22 (2), 18–27.

Azevedo, A.L., Toscano, C., and Sousa, J.P., 2005. Cooperative planning in dynamic supply chains. *International Journal of Computer Integrated Manufacturing*, 18 (5), 350–356.

Barbarosoglu, G. and Özgür, D., 1999. Hierarchical design of an integrated production and 2-echelon distribution system. *European Journal of Operational Research*, 118 (3), 464–484.

Bhatnagar, R., Chandra, P., and Goyal, S.K., 1993. Models for multi-plant co-ordination. *European Journal of Operations Research*, 67 (2), 141–160.

Calosso, T., *et al.*, 2003. Production planning and order acceptance in business to business electronic commerce. *International Journal of Production Economics*, 85 (2), 233–249.

Chen, H. and Chu, C., 2003. A Lagrangian relaxation approach for supply chain planning with order/setup costs and capacity constraints. *Journal of Systems Science and Systems Engineering*, 12 (1), 98–110.

Cloutier, L., *et al.*, 2001. A commitment-oriented framework for networked manufacturing co-ordination. *International Journal of Computer Integrated Manufacturing*, 14 (6), 522–534.

D'Amours, S., Montreuil, B., and Soumis, F., 1997. Price-based planning and scheduling of multiproduct orders in symbiotic manufacturing networks. *European Journal of Operational Research*, 96 (1), 148–166.

Davis, R. and Smith, R.G., 1983. Negotiation as a metaphor for distributed problem solving. *Artificial Intelligence*, 20 (1), 63–109.

Dudek, G. and Stadtler, H., 2005. Negotiations based collaborative planning between supply chain partners. *European Journal of Operational Research*, 163 (3), 668–687.

Dudek, G. and Stadtler, H., 2007. Negotiation based collaborative planning in divergent two-tier supply chains. *International Journal of Production Research*, 45 (2), 465–484.

Erengüc, S.S., Simpson, N.C., and Vakharia, A.J., 1999. Integrated production/distribution planning in supply chains: An invited review. *European Journal of Operational Research*, 115 (2), 219–236.

Ertogral, K. and Wu, D.S., 2000. Auction-theoretic co-ordination of production planning in the supply chain. *IIE Transactions*, 32 (10), 931–940.

Forget, P., D'Amours, S., and Frayret, J.-M., 2008. Multi-behavior agent model for planning in supply chains: An application to the lumber industry. *Robotics and Computer-Integrated Manufacturing*, 24 (5), 664–679.

Fox, M.S., Barbuceanu, M., and Teigen, R., 2000. Agent-oriented supply-chain management. *International Journal of Flexible Manufacturing Systems*, 12 (2–3), 165–188.

Frayret, J.-M., *et al.*, 2007. Agent based supply chain planning in the forest products industry. *International Journal of Flexible Manufacturing Systems*, 19 (4), 358–391.

Frayret, J.-M., *et al.*, 2001. A network approach to operate agile manufacturing systems. *International Journal of Production Economics*, 74 (3), 239–259.

Frayret, J.-M., D'Amours, S., and Montreuil, B., 2004. Co-ordination and control in distributed: An agent-based manufacturing systems. *Production Planning & Control*, 15 (1), 465–484.

Gaudrealt, J., Frayret, J.-M., and Pesant, G., 2009. Distributed search for supply chain co-ordination. *Computer Industry*, 60 (6), 441–451.

Hax, W.E. and Meal, H.C., 1975. Hierarchical integration of production planning and scheduling. *In*: M.A. Geisler, ed. *Logistics: studies in the management sciences*. Amsterdam: North-Holland, 53–69.

Holmgren, J., Persson, J., and Davidsson, P., 2009. Agent-based Dantzig-Wolfe decomposition. *LNCS, Agent and Multi-Agent Systems: Technologies and Applications*, 5559 (1), 754–763.

Hu, Q., Kumar, A., and Zhang, S., 2001. A bidding decision model in multiagent supply chain planning. *International Journal of Production Research*, 39 (15), 3291–3301.

Jennings, N.R., *et al.*, 2001. Automated negotiation: prospects, methods and challenges. *Group Decision and Negotiation*, 10 (2), 199–215.

Jung, H. and Jeong, B., 2005. Decentralised production-distribution planning system using collaborative agents in supply chain network. *International Journal of Advanced Manufacturing Techniques*, 25 (1–2), 167–173.

Lee, S. and Kumara, S., 2007. Decentralised supply chain co-ordination through auction markets: dynamic lot-sizing in distribution networks. *International Journal of Production Research*, 45 (20), 4715–4733.

Pibernik, R. and Sucky, E., 2007. An approach to inter-domain master planning in supply chains. *International Journal of Production Economics*, 108 (1–2), 200–212.

Poundarikapuram, S. and Veeramani, D., 2004. Distributed decision-making in supply chains and private E-marketplaces. *Productions and Operations Management*, 13 (1), 111–121.

Schneeweiss, C., 2003. Distributed decision making: A unified approach. *European Journal of Operational Research*, 150 (2), 237–252.

Silva, C.A., *et al.*, 2006. Distributed optimisation of a logistic system and its suppliers using ant colonies. *International Journal of Systems Science*, 37 (8), 503–512.

Stadtler, H., 2009. A framework for collaborative planning and state-of-the-art. *OR Spectrum*, 31 (1), 5–30.

Taghipour, A., 2009. Évaluation de la collaboration dans une chaîne d'approvisionnement. *Revue française de gestion industrielle*, 28 (1), 25–42.

Taghipour, A. and Frayret, J.-M., 2010. Negotiation based co-ordination in supply chain: model and discussion. *IEEE Transactions SMC*, 1 (1), 1643–1649.

Taghipour, A. and Frayret J.-M., 2011a. Supply chain co-ordination planning: A review. Work paper. École polytechnique de Montréal.

Taghipour, A. and Frayret, J.-M., 2011b. Mutual adjustment search with incentive for supply chain planning co-ordination. *International Journal of Computer Integrated Manufacturing*, 25 (10), 946–962.

Uster, H., *et al*., 2007. Benders decomposition with alternative multiple cuts for a multi-product closed-loop supply chain network design model. *Naval Research Logistics*, 54 (8), 890–897.

Váncza, J., Egri, P., and Monostori, L., 2008. A co-ordination mechanism for rolling horizon planning in supply networks. *CIRP Annals – Manufacturing Technology*, 57 (1), 455–458.