Tactical Management for Coordinated Supply Chains

Miguel Zamarripa, Kefah Hjaila, Javier Silvente and Antonio Espuña*
Chemical Engineering Department, Universitat Politècnica de Catalunya, ETSEIB. Diagonal Avenue 647, 08028 Barcelona, Spain.
*corresponding author: antonio.espuna@upc.edu

Abstract

Current Supply Chain (SC) optimization models deal with material and information flows along few echelons of the SC ("own SC"), minimizing the role of the complex behavior of third parties (raw materials and utilities suppliers, clients, waste and recovery systems, etc.) in the decision-making process of this SC of interest. Third parties are just represented by simplified parameters (capacity, cost, etc.) usually considered constant, but the decisions based on this picture are not adequate when the third parties' behavior is significantly affected by these decisions or other circumstances, especially when global coordination is attained. In this work, the role of these third parties, which might face different objectives, has been integrated and a solution based on the full SC management problem is proposed. This results on a generic model which may be used to optimize the planning decisions of the multi-product multi-site SC of interest (production/distribution echelons), taking into account the production vs. demand coherence among this SC and the third parties. The features of the proposed model are illustrated using a case study which considers the coordination of a series of resource (energy) generation SCs linked to a production/distribution SC ("SC of interest"). The results show how the behavior of the considered SCs determines the best planning decisions of each organization, which will depend on the way used to coordinated them (e.g. towards less total or individual costs), adding to the PSE science a new point of view which allows all involved organizations to share responsibilities in the system.

Keywords: Supply Chain, Tactical Management, Supply Chains Coordination, SCM

1. INTRODUCTION

Current changes in the way to run business around the world open the door for new issues to be considered in the Supply Chain Management (SCM) models and procedures, including environmental considerations, new market trends, decision making under uncertainty, and market globalization. Typical SCM approaches consider single SC material flow information to improve the decision making (DM) process at the strategic, tactical, and/or operational DM levels, and their capacity to deal with these new issues depends not only on the possibility to incorporate new information and models associated to the internal organization (i.e. environmental assessment information, financial models, etc.), but also on the ability to correlate current and new working information with the behavior of the SC working scenario (i.e. price negotiation, demand elasticity, etc.).

Regarding strategic decision making, multiple approaches have been published considering several potential suppliers, production plants, and distribution centers to serve some fixed markets. Higher complexity scenarios, like the resulting from the consideration of flexible operation among the SC network, with multiple retailers and distribution centers serving others under uncertain market demands, have been also successfully addressed (Shu *et al.*, 2005).

On the tactical DM level, Tsiakis and Papageorgiou (2008) provided optimal product site allocation among sites with outsourcing availability for multi-product multi-site networks. Furthermore, Susarla and Karimi (2012) presented a mixed integer linear programming (MILP) model to find the optimal procurement, production, and distribution levels for a large scale multi-site multiproduct network (multinational pharmaceutical SC with 34 entities producing 9 different products).

Operational applications, including single stage facilities for multiproduct, multi-task and batch processes, have been also covered (Castro *et al.,* 2008; Castro and Grossmann, 2012). In addition, multi stage facilities have been considered by Prasad and Maravelias (2008).

Nevertheless, in order to deal with the problem of managing a competitive SC facing a global market, the coordination of its echelons (acquisition of raw material, production sites, warehouses, and markets) with their supporting external SCs is needed at the planning level, and formulations including multiple SCs coordination are weakly dealt up today, especially if a detailed production-storage-distribution plan is to be established.

In this sense, after an extensive Process Systems Engineering (PSE) literature review, three main issues have been identified which, even they have been object of interest of the scientific community in the last years, still require specific attention:

(i) Multiple Objective Optimization: the consideration of multiple objectives regarding market, social, and other external or internal issues currently justify introducing new elements related to environmental and risk regimes as part of the SCM objectives together with the economic performance. The need to consider the resulting trade-offs among those different objectives changes the way to deal with the decision making problem (Nagurney *et al.*, 2005; Guillén-Gosálbez *et al.*, 2005; Bojarski *et al.*, 2009; Guillén-Gosálbez and Grossmann, 2010; Dugardin *et al.*, 2010; Park and Shin, 2012; Lin *et al.*, 2013), but the specific incorporation of third parties' objectives in the DM procedure should be analyzed in depth.

(ii) Uncertainty management: one basic characteristic of the SC planning problem is the presence of uncertainty coercing the "here and now" decision making. This uncertainty may affect the expectations about the raw materials supply and/or the market behavior (demand, prices, delivery requirements, etc.), as well as other internal elements (i.e. operating parameters like lead times, transport times, etc., or the availability of production resources). A literature review on this topic reveals that most of the systematic tools currently available to manage decision making under uncertainty have been proposed to address the SC planning problem. In this line, it is worth to mention the use of Model Predictive Control (Bose and Penky, 2000), Multi-Parametric Programming (Wellons and Reklaitis, 1989; Dua *et al*., 2009), Fuzzy Linear Programming (Peidro *et al*., 2010) and specially Stochastic Programming (Gupta and Maranas, 2003; Haitham *et al*., 2004; You and Grossmann, 2010; Amaro and Barbosa-Póvoa, 2009; Baghalian *et al*., 2013; Klibi and Martel, 2012). If the effects of the uncertainty can be minimized through the management of a reduced number of variables, the use of simulation-optimization based approaches may constitute a practical way to circumvent the complexity of the above mentioned mathematical formulations of the problem, as proposed by Jung *et al*., (2004) to determine the required safety stock levels to maintain client satisfaction when facing some expected uncertain demand behavior. Nevertheless, uncertainty is not always associated to the effect of random events (white noise), since it might also reflect the difficulties to incorporate already existing information and models in the problem formulation (e.g.: information related to consumers/suppliers behavior), so in these cases the costs, effort and potential benefits of integrating this information in the decision making model should be analyzed.

(iii) Coordinated Management: this term has been widely used in the literature as related to different management problems, since its scope has not been clearly limited. For example, in the marketing literature, some interesting applications show coordination schemes related to pricing decisions taking into consideration deterministic and uncertain demands. This is the case of the work of Xiangtong *et al.,* (2004), who solved the tactical management of one-supplier one retailer SC with uncertain demands in the model formulation. Two specific SC coordination management problems are worth to be mentioned at this point:

(a) The most widely studied topic in the area of coordinated management is focused to vertical integration. The necessity to ensure coherence among different decisions, usually associated to different time and economic scales, is one of the main complicating points in modeling and solving the SC management problem. In this regard, many currently proposed approaches are based on the development of design-planning models (Laínez *et al.*, 2009; Cardoso *et al.*, 2013; Kopanos *et al.,* 2011), while others focused on the integration of midterm decision making levels using integrated planning-scheduling models (Sung and Maravelias, 2007; Guillén-Gosálvez *et al.*, 2006: Kopanos *et al.,* 2012) and/or production-distribution planning models (Cóccola *et al.*, 2013; Erengüç *et al.*, 1999). But there are still many issues to be solved before the proposed methods and tools may be considered as practical solutions to the problems observed in industrial practice.

(b) Another type of coordination management problem which has raised interest in the academic community is the one associated to Closed Loop SCs, which extends the typical SCM scope in order to allow the integration of used products/wastes into the economic cycle (Fröhling *et al.*, 2010). To address this situation, the model formulation must include a reverse channel to locate the new remanufacturing, reprocessing and reusing activities and, especially, to introduce the new interactions among SC echelons resulting from these activities (Atasu *et al.*, 2008). The demand is therefore satisfied by a mix of new and remanufactured products (Georgiadis and Athanasiou, 2013). Several benefits might be considered as associated to the adequate management of these re-used products, including the reduction of the environmental damage (Chi *et al.*, 2011), the fulfillment of government incentives (Wei-Min *et al.*, 2013), etc. The explicit integration of uncertainty has been also considered in multi-period multiproduct networks with reverse flows for strategic and tactical decision making (Salema *et al.*, 2007 and 2010, respectively).

Model based decision-making methods and tools have been systematically applied to solve most of the different SC topics which may be identified as coordination management problems, like the ones just mentioned. But in general SC networks, the description of the relations between entities, and so their coordination, usually lead to very complex mathematical models, so its optimization requires the use of more generic tools, like is the case of multi-agent systems.

Multi-agent systems can be defined as software based computer entities with certain characteristics (Wooldridge and Jennings, 1995): Autonomy (flexibility over its actions), social ability (agents interact with other agents), reactivity (agents perceive their environment) and pro-activeness (agents are able to exhibit goal-directed behavior). The coordination of multi-agent systems emulates the negotiations among the different participating SC entities towards their specific objectives, so multi-agent systems have been widely applied to SCM in the last decade, as a way to analyze the coordination among purchase, production, inventory, and vehicle routing activities (e.g.: Moyaux *et al.,* 2006). The use of multi-agent systems is especially convenient when there is a need for cooperation (coordination) among different SC echelons, as is the case presented by Cao *et al.,* (2007), who proposed a Pinch Multi-Agent Genetic Algorithm (PMAGA) model to optimize water-using networks; in their resulting NLP model, all agents cooperatively try to minimize the total freshwater needed for the process based on water-contaminant mass balance constraints. For SC planning problems, Banaszewski *et al.,* (2013) developed a multi-agent auction-protocol model for the planning of a Brazilian oil supply chain; the coordination appears through the negotiations among different interacting agents representing each participating entity; their model is based on defining the bid values and the sequence of auction commitments in order to avoid conflicts in the allocation of common resources (i.e. tanks, arcs, etc.). Yuan *et al.,* (2013) proposed a multi-agent stochastic optimization model in which different agents minimize the sum of their objective functions cooperatively based on global inequality constraints and global convex constraints.

In all these contributions, SCM focuses on the SC echelons directly linked to the process of interest (suppliers, production sites, distribution centers, markets), disregarding the detailed characteristics of the input flows to such enterprises (echelons). By doing so, much information is lost: the enterprises participating in the entire SC are not clearly represented in the planning model and, as a result, the impact of each enterprise decisions on the others is not explicitly considered. In this way, for example, maximizing enterprise benefits without considering the goals of the other SCs might result in globally sub-optimal decisions (Moyaux *et al.,* 2006).

In a previous work, Zamarripa *et al.,* (2012) presented a tactical decision making model to assess multiple SCs' behavior under cooperation and competition scenarios, demonstrating how coordinating SCs is necessary for robust decision making, and also how the knowledge about third parties' policies might be exploited to deal with competitive markets and enterprises. Further developing the concept of "coordinated management", this paper aims to optimize the tactical management of multiple SCs as one "entire coordinated SC": the behavior of each echelon is characterized as a SC, with its objectives and management practices, so it is feasible to integrate the different resulting policies and to apply cooperative decision making tools, leading to a planning model able to coordinate the supply/production-storage-distribution/market echelons under an integrated objective (e.g.: "to minimize the total cost" of the entire SC) or, alternatively, using a multi-objective approach. The main characteristics of the entire system (raw materials SC, production-distribution SC, products, and wastes) have been considered and, consequently, the optimal tactical decision making identifies the best way to coordinate the production, distribution and storage levels of the entire SC.

2. Problem statement and modeling strategy

Typical supply chain planning problem statement (e.g.: long term planning: Jackson and Grossmann, 2003; or short term planning: Kopanos *et al.*, 2012) takes into account a few number of echelons (usually suppliers, production plants, distribution centers, and markets) and consider that the external interactions among such echelons are characterized through some fixed data (production capacity, demand, etc.). Assuming this usual planning problem statement, this work aims to extend its scope by including detailed information of each echelon in such a way it might be potentially managed as a complete SC with multiple echelons.

2.1 Mathematical model

The proposed framework is based on developing a coordinated planning model by integrating the information of several SCs among one entire SC. So it allows to introduce the detailed characteristics of each SC individual structure/echelons, as for example including suppliers' SCs and their related production plants, which in turn may include other suppliers, etc. For this purpose, one of the main characteristics of the proposed formulation is its flexibility to accept different simultaneous partitions (SC assignments) and flexible limits in the systems to be considered: each echelon is able to simultaneously play different roles (e.g.: market in one SC, supplier in another SC, and distribution center in the entire SC) according to the specific structure to be optimized. In this sense, the proposed model includes the typical sets of products, distribution centers, production plants, and markets but, in order to represent the expected way of coordinating the different elements to be now considered (multiple SCs interacting among them), a set of supply chains (s= 1, 2, …, SC) and their corresponding new subsets linking each product, distribution center, production plant, and market, have been considered into the formulation. The main function of the subsets is to flexibly assign the sets of elements (plant/product/distribution center/ market) to their corresponding SC. Discrete time formulation has been considered with a time horizon T.

The model, as presented in this section, is composed by several constrains representing mass/energy/economic balances, production/storage/distribution relations and maximum/minimum capacities. In a first approach, all these constraints can be simplified through linear relations among the decision variables, resulting in a LP planning system able to deal with the complexity arising when different SCs, with their independent characteristics and objectives, interact. As a result, the proposed system to deal with this problem is composed by the following elements:

The minimum and maximum availability levels of raw materials (supplier's capacity), production, and storage limits are considered as constraints among the generated model (Eq. 1, 2, and 3, respectively); no storage constraints are considered for markets and suppliers, as far as they are considered external to the supply chain of interest (M and N sets respectively, whose composition will depend on the specific study to be developed).

$$prd_{r,e,t}^{min} \leq \sum_{\substack{e' \in E \\ e' \neq e}} DLV_{r,e,e',t} \leq prd_{r,e,t}^{max} \; \forall \, r \in R, e \in N \,, t \in T \qquad 1$$

$prd^{min}_{r,e,t} \leq PRD_{r,e,t} \leq prd^{max}_{r,e,t} \; \forall \, r \in R, e \in E \,, t \in T$	2
$sto^{min}_{r,e,t} \leq STO_{r,e,t} \leq sto^{max}_{r,e,t} \; \forall \, r \in R, e \in \{E - N - M\} \,, t \in T$	3

Equations (4a) and (4b) specify the material balance at each echelon. The incoming products plus the previously stored products minus the products distributed to the final markets must be equal to the storage level at each time period.

In order to take into account the coordination of several supply chains production/consumption, the internal demand is considered in Eq. (4a), (4b) as a function of the production levels. Those production levels are associated to internal requirements (energy, waste water, intermediate products, maintenance, etc.), which in turn are characterized as demand of the products developed by other SC echelons. These production levels are multiplied by a production factor $prf_{\mathrm{r,r',}e}$which considers the specific needs of the utilized recipe, so this equation represents the production vs. demand coherence when coordinating different SCs, as any echelon may act simultaneously as market of other SCs along the entire considered system (global SC). The extension of the model in order to consider (and select) different production recipes/costs in each production echelon is straight forward.

$STO_{r,e,t} = st0_{r,e} + \sum_{\substack{e' \in E \\ e' \neq e}} DLV_{r,e',e,t} + PRD_{r,e,t} - \sum_{\substack{e'' \in E \\ e'' \neq e}} DLV_{r,e,e'',\mathrm{t}} - \sum_{\substack{r' \in R \\ r' \neq r}} prf_{\mathrm{r,r'},e} \cdot PRD_{\mathrm{r'},e,\mathrm{t}} \qquad \forall \, r \in \mathrm{R}; e \in \mathrm{E}; \mathrm{t} = 1$	4a
$STO_{r,e,t} = STO_{r,e,t-1} + \sum_{\substack{e' \in E \\ e' \neq e}} DLV_{r,e',e,\mathrm{t}} + PRD_{r,e,t} - \sum_{\substack{e'' \in E \\ e'' \neq e}} DLV_{r,e,e'',\mathrm{t}} - \sum_{\substack{r' \in R \\ r' \neq r}} prf_{\mathrm{r,r'},e} \cdot PRD_{\mathrm{r'},e,\mathrm{t}} \qquad \forall \, r \in \mathrm{R}; e \in E; \; t > 1$	4b

The total external market demand (Eq. 5) must be satisfied from the distribution centers and other connected echelons ($DLV_{r,\mathrm{e,e'},t}$). Other service policies may be also easily considered with just a slight modification in this constrain and/or by introducing penalty costs, as proposed in eq. 11b).

$\sum_{\substack{e \in E \\ e \neq e'}} DLV_{r,\mathrm{e,e'},t} \geq dmd_{r,\mathrm{e'},t} \; \forall \, e' \in M; r \in R \,; t \in T$	5

The total cost of the entire system along the considered production horizon will be calculated as noted in Eq. 6. The production cost (CPR_t) is computed based on the variable cost (charge level) in each production plant (Eq. 7). Moreover, acquisition cost of the externally supplied resources (CRM_t) is calculated by considering the quantity of resources (raw material, energy,…) needed for the production processes (Eq. 8). The storage cost (Eq. 9) is considered proportional to the amount of resources (raw material, intermediate products, final products pending of delivery, etc.) stored each time period in each echelon. Finally, the distribution costs (Eq. 10) are calculated considering the distance between the different echelons and some unitary transport cost which will depend of the product, the specific route, etc.

$$COS = \sum_{t \in T} (CPR_t + CRM_t + CST_t + CTR_t) \tag{6}$$

$$CPR_t = \sum_{r \in \mathrm{R}} \sum_{e \in \mathrm{E}} vpr_{r,\mathrm{e},t} \cdot PRD_{r,\mathrm{e},t} \ \ \forall\, t \in T \tag{7}$$

$$CRM_t = \sum_{r \in \mathrm{R}} \sum_{e \in \mathrm{N}} \left(val_{r,e,t} \cdot DLV_{r,e,t} \right) \ \forall\, t \in T \tag{8}$$

$$CST_t = \sum_{r \in \mathrm{R}} \sum_{e \in \mathrm{E}} \left(vst_{r,e,t} \cdot STO_{r,e,t} \right) \ \forall\, t \in T \tag{9}$$

$$CTR_t = \sum_{r \in \mathrm{R}} \sum_{e \in \mathrm{E}} \sum_{\substack{\mathrm{e}' \in E \\ \mathrm{e}' \neq \mathrm{e}}} \left(dis_{e,\mathrm{e}'} \cdot vtr_{r,e,\mathrm{e}'} \cdot DLV_{r,e,\mathrm{e}',\mathrm{t}} \right) \ \forall\, t \in T \tag{10}$$

Moreover, sales are computed by multiplying the retailed price of the final product by the quantity of products required by the external markets (Eq. 11). Although additional delivering might be admitted (current form of Eq. 5), its eventual benefit is not included, so the optimization will drive the solution to meet just the external demand requirements (cost minimization objective). Alternatively, different ways to penalize the eventual mismatch among external demand and deliveries may be easily incorporated (Eq. 11b).

$$SAL = \sum_{t \in T} \sum_{r \in R} \sum_{e \in \mathrm{M}} val_{r,e,t} \cdot dmd_{r,e,\mathrm{t}} \tag{11}$$

$$SAL = \sum_{t \in T} \sum_{r \in R} \sum_{e \in \mathrm{M}} \left[vpy_{r,e,t} \cdot dmd_{r,e,\mathrm{t}} + (val_{r,e,t} - vpy_{r,e,t}) \sum_{\substack{\mathrm{e}' \in \mathrm{E} \\ \mathrm{e}' \neq \mathrm{e}}} DLV_{r,\mathrm{e}',e,\mathrm{t}} \right] \tag{11b}$$

Finally, the total profit of the entire SC (Eq. 12) is calculated as the difference between the total sales and the total costs.

$$PFT = \mathrm{SAL} - \mathrm{COS} \tag{12}$$

These equations, in their current form, constitute a LP model which may be applied to the complete system (as now written) or to any subset of echelons, just considering the resulting specific sets M_s and N_s instead of the global sets M and N. In this case, it is worth noting that M_s and N_s will not necessarily correspond to subsets of their respective global sets since, as previously mentioned, the formulation takes into account that any echelon may operate as market and/or supplier of any other echelon and so, the qualifier of "external" depends on the limits of the considered SC.

This very simplified model can be easily extended if discrete decisions are required (e.g. allocation of production and distribution elements which should maintain a minimum activity level or else to be considered totally inactive), leading to a MILP model. Moreover, the flexibility of the proposed formulation allows to introduce simple modifications to consider more realistic interactions among SCs such as: (i) non-linearities on the relations between the quantities of required external resources and their unitary prices; (ii) coordination under uncertainty in the forecasts of external demands, market prices, resources availability, etc. (scenario behavior) and/or in the forecast of the relations between the considered variables (e.g. negotiation limits among echelons of different SCs); and (iii) multiple objective analysis, including the consideration of local objectives of individual SCs. The consideration of these more complex interactions is straightforward just following any of the methods already referenced in the introductory section as applicable in such situations although, accordingly, more sophisticated PSE tools will be needed to solve the resulting more complex mathematical models.

3. Case Study

The concepts described above have been applied to case study at pilot plant scale, in order to demonstrate the kind of results which can be derived from the mathematical model presented. The case study includes a main production-distribution SC (PDSC, in this case based on a typical polystyrene production system) and an energy generation SC (EGSC), which will be coordinated as one complete SC.

3.1 Polystyrene production-distribution SC (PDSC)

The polystyrene production-distribution SC includes a set of 4 suppliers (*sp_s1, sp_s2, sp_s3, sp_s4*), 3 production plants (*pl_sl, pl_s2, pl_s3*), 2 distribution centers (*dc_s1, dc_s2*), and 4 markets (*mk_s1, mk_s2, mk_s3*) as indicated in Fig. 1.

Fig. 1. Polystyrene production echelon SC network

The main resource used for polystyrene production (raw material – RM) is a mix of styrene and catalyst, which has been considered available in 4 different forms/prices (*rm_s1, rm_s2, rm_s3, rm_s4*). Each production plant may produce 2 final products (*pr_s1* and *pr_s2*); the main difference between these two products is its conversion degree, which is 99% for *pr_s1* and 97% for *pr_s2*. The first polymer (*pr_s1*) requires more production time as well as more energy to be produced than the second polymer (*pr_s2*). In this product, and between the considered production limits, it has been considered that a higher conversion degree involves more quality in the characteristics of the product in terms of its thermo-mechanical properties, and that this justifies a different (higher) market price. The minimum values for RM supply capacity, storage and production capacity have been accepted to be zero for all entities and time periods, allowing a significant reduction of the mathematical complexity of the problem. The storage cost of each polystyrene type in each distribution center is considered to be *0.001 €/(kg·day)*, for all time periods. The transportation cost is considered to be *0.0010 €/(kg·km).*

The objective consists on making the adequate planning decisions to optimize the SC performance (production, inventory, distribution levels; production/distribution/storage levels; RM supplying, etc.). The characterization parameters of the PDSC model are summarized in Tables A1 to A8 (Appendix A).

3.2 Energy Generation SC (EGSC)

Nowadays, biomass is ranked as the fourth energy production source after oil, gas and coal, providing approximately 14% of the world's energy needs (García *et al.,* 2012). Electricity generation based on biomass gasification and combustion has been significantly developed over the last few years, demonstrating its great market potential.

For this study, different biomass sources and coal are considered to be potentially used as raw materials (RMs), feeding the 6 energy generation plants of interest: 3 gasification plants (*pl_e1*, *pl_e2* and *pl_e3*) and 3 combustion plants (*pl_e4, pl_e5* and *pl_e6*). Each one of these elements (EGSC) consists of a RM supplier echelon and an energy production-distribution echelon (Fig. 2).

One supplier *sp_e1* is responsible for providing these different available RMs (wood pellets-*rm_e1*, coal-*rm_e2*, petcock-*rm_e3*, and marc waste-*rm_e4*), which exhibit different characteristics, costs and energy generation rates (*0.7-2.0 kWh/(kg RM)* for the gasification processes and *1.5-2.6 kWh/(kg RM)* for the combustion processes, depending on the specific RM used). A certain proportion of wastewater will be generated per kWh produced (the same rate is assumed for all considered plants: *14.7 kg/kWh*, as reported by Martínez, 2011), and the energy required for its treatment processes is calculated according to a rate of *0.00043 kWh/kg.*

Fig. 2. a) Energy RM echelon b) Energy production-distribution echelon

The RM is purchased from the supplier and transported and stored in the energy plants. Accordingly, the RM echelon SC takes into account RM acquisition, transport, and storage steps. Table 1 and Table 2 show the involved parameters: The RM purchasing cost will depend on the specific market conditions, as described in the work of Pérez-Fortes *et al.,* (2011), although this dependence has been neglected in this case-study. The RM storage cost has been taken from LaTourrette *et al.,* (2011). Maximum, minimum, and initial biomass storage capacities have been assumed as indicated in Table 1. The RM transportation cost to the energy plants is considered to be *0.0002 €/(kg·km)*.

Table 1. EGSC parameters (supply echelon)

Table 2. Distance between RM supplier and the energy plants

Figure 2b shows the detailed energy production-distribution SC echelon. The energy production cost using a downdraft fixed bed gasification processes and a gas turbine is about *0.26 €/kWh* , and typical production cost using a combustion process and a steam turbine is *0.13 €/kWh* (Obernberger and Thek, 2008). Accordingly, the production costs using the different RM types have been assumed around these numbers. Electricity production ratio using wood pellets, petcoke, and marc waste have been based on the results of Martínez (2011). The electricity production ratio using coal is based on ©Hudson Oil Corporation Report Ltd. (2011) (Table 3).

Table 3. EGSC parameters (production echelon)

3.3 Coordination strategy

The principal function of the PDSC, as well as the one of the entire SC, is to produce polystyrene to satisfy different market demands according to certain nominal patterns (Table 4). Six energy plants using different technologies (combustion and gasification) are considered to generate energy to serve the polystyrene plants (*pl_s1… pl_s3,* corresponding to mk*_e1… mk_e3*). Two energy plants are associated to each polystyrene production location, and the local polystyrene plants (with their local wastewater treatment plants, WWTP) are their natural energy markets (Fig. 3), while other two additional energy markets (*mk_e4* and *mk_e5*) can be also considered although, for the purpose of this study, they are considered external and exhibit a certain demand pattern (Table 5) which is not object of negotiation.

Table 4. Polystyrene production demands

Table 5. External energy demands

Fig. 3. The entire SC scheme

The wastewater generated at each production location (including the wastewater generated in the polystyrene process and the local energy plants) is assumed to be treated inside the corresponding location. Thus, the energy needed for the treatment process will be added to the energy needed for polystyrene production when computing the total energy requirements (wastewater and polystyrene plants).

The local electricity grid may also serve energy to the polystyrene plants (Fig. 4). On the other hand, besides providing energy to the markets, energy production plants have the flexibility to sell energy to the local electricity grid. The price of the energy purchased from the electricity local network is assumed to be *0.40 €/kWh*, while the sales price to the local electricity network is assumed to be *0.30 €/kWh*.

Fig. 4. Energy flows among the entire SC

4. Results and discussion

The proposed planning LP model has been solved taking into consideration material and energy flows, processes availability, constraints, and distribution tasks over a time horizon of 10 time periods of 300 working hours each. The resulting model identifies the optimal performance of each echelon SC among the entire SC. In order to highlight the advantages of the proposed approach, the optimal planning decisions (RM acquisition, storage, production, and distribution) have been obtained for two scenarios: a) Non-coordinated SCs: each SC (Biomass SC, EGSC, PDSC) has been solved separately and the total cost of each one is obtained. b) Coordinated SCs: each partial SC is coordinated with each other forming the entire SC model, and thus the total cost of the entire coordinated SC is obtained. The main objective function in both scenarios is to minimize the respectively involved total cost: in the first scenario, the total cost of the separate echelons SCs are minimized, while the second scenario aims to minimize the total cost of the coordinated entire SC. A comparison between the planning decisions for both scenarios will take place in the following sections to point out the potential of the SCs coordination.

From a computational point of view, the model discussed in section 2 has been implemented in GAMS using CPLEX (12.5) on a Windows XP computer with Intel® Core^{tm} i7 CPU(920) 2.67 GHz processor with 2.99 GB of RAM. The non-coordinated scenario results into a model of 3,262 single equations, 5,011 single variables and it is solved in <1 CPU seconds. The coordinated scenario results on a model with 3,264 equations and 5,023 single variables and also requires <1 CPU seconds.

4.1 Non-coordinated scenario

Since the PDSC is the main SC of the problem, in this case it will be solved without considering the EGSC needs, so the theoretical energy needed to optimize this part will be computed. As consequence, the polystyrene SC has been solved separately to fulfill the polystyrene market demands at a minimum cost. Accordingly, the typical decisions behavior is expected to be in favor of the cheapest RM and the least distribution cost (distance between supplier-production plants-distribution centers-markets).

Fig. 5. Production levels (non-coordinated system)

Fig. 5 shows how the production levels vary in the production plants (*pl_s1, pl_s2*, and *pl_s3*). The production plant *pl_s2* dominates the polystyrene production (*pr_s1, pr_s2*), due to its lowest distribution distance to the preferred suppliers (*rm_s2* and *rm_s3*). It has been noticed that the production plant *pl_s1* is working at *t4* (Fig. 5) due to the highest demand at this time period. In order to reduce the expenses, the system proposes to produce at *t1-t3* from *pl_s2* and *pl_s3* more than the quantity demanded at these time periods meanwhile storing the excess (Fig. 6) to be distributed at *t4* (same case at *t8*).

Fig. 6. Inventory levels (non-coordinated system)

Once the PDSC model has been solved, the energy required to reach the polystyrene production levels is computed (see, Fig. 7) to be introduced later as fixed demands (*mk_e1* to *mk_e3*) for the non-coordinated EGSC model.

Fig. 7. Energy required by the PDSC (non-coordinated system)

After introducing all energy markets demands, the EGSC model has been solved. The best solution is again in favor of using the RM of lowest cost, considering price and distribution costs as well as energy production efficiency. In this case, coal is found as the best RM solution. Regarding the energy production, and according to the market demands, the load is higher on systems *pl_e2*, *pl_e3*, *pl_e5*, and *pl_e6*. The performance of the EGSC can be observed in Figs. 8 and 9. Figure 8 shows how the production levels are distributed among the production plants. The energy distribution to the markets can be observed in Fig. 9. Most of the energy production comes from the combustion plants *pl_ e5* and *pl_ e6*, till reaching their maximum capacities. When the demand exceeds the capacity of the combustion plants, the gasification process is used to cover the rest. In case the demand is even higher than the EGSC production capacity, the local electricity grid is also used.

Fig. 8. Energy production levels (non-coordinated system)

Fig. 9. Energy distribution plan (non-coordinated system). *mk_e4* and *mk_e5* correspond to external markets

Fig. 10. Acquisition of EGSC raw materials (non-coordinated system)

Fig. 10 shows the optimal acquisition levels of the RMs needed for the energy plants. Such a behavior meets with the energy production levels patterns (Fig. 8). It is worth mentioning here that all the RM amounts appearing in Fig. 10 belong to coal (*rm_e2*).

Analyzing the results obtained from this typical non-coordinated scenario, two main points should be highlighted:

- In case the polystyrene production plants *pl_s2* and *pl_s3* need more energy, this will cause more pressure on the EGSC energy plants to produce more, till reaching their limits. In this case, this even implies the need to buy energy from the local electricity grid and thus the total cost will be highly increased.
- Based on this point, the EGCS energy plants (*pl_e5* and *pl_e6*) will need more RM and thus this will affect the supplier, who will become close to reach its capacity.

Common sense clearly indicates that, if the knowledge of the EGSC was considered when producing polystyrene, the polystyrene production-distribution orders would be different: The information of the EGSC, together with its RM SC, will be introduced as a complete SC, with its behavior and objective function, to the PDSC. Both will be coordinated together to form one “entire SC” model.

Accordingly, the demands for *pl_e1… pl_e6* become variable based on the polystyrene production patterns, and another assessment of the resulting scenario solution should be expected.

4.2 Coordinated SCs

In the coordinated scenario, the tactical decision making of the entire SC is optimized. The proposed model explicitly includes the knowledge of both SC's. Same polystyrene markets demands as in the non-coordinated scenario are considered, and the results show the difference between the planning decision orders of the EGSC and PDSC for both scenarios.

Figure 11 shows the production levels of the PDSC when coordinated with the EGSC. All polystyrene production plants are working for the first four time periods to produce *pr_s1*, while *pl_s1* and *pl_s3* dominate producing *pr_s2* in all time periods. The production and storage orders have been reallocated to achieve the markets demands as well as to reduce the work load on the EGSC.

Fig. 11. Polystyrene production (coordinated system)

Polystyrene storage levels of the coordinated PDSG encountered new changes due to coordination SCs. For example, distribution center *dc_s2* was just used in the time period *t8*, while now it is used for more time periods (Fig. 12).

Fig. 12. Inventory levels of PDSC (coordinated system)

Fig. 13. Energy required by PDSC plants (coordinated system)

As it is described in the problem formulation, the cooperative model computes the energy required by the PDSC plants (dynamic markets). The optimal production-distribution of energy is then considered among the entire SC network. In this case, the optimal results show how the work load of the polystyrene plants has been distributed (Fig. 13), in comparison with the non-coordinated case (Fig. 7) by reducing the energy consumption from plant *pl_s2* (*mk_e2*) and plant *pl_s3* (*mk_e3*) and including the production plant *pl_s1* (*mk_s1*) in the production plan.

Since the scope of the typical production planning approach has been extended, a quite different SC behavior can be obtained. The coordinated model shows that the optimal solution in this extended scope is far away from the previously found local optimal solution. Fig. 14 shows the energy generation levels, indicating how the "entire SC" reaches the most profitable energy production and, then, the production of polystyrene is adapted in order to use the cheapest energy sources (other plants are used to avoid the use of the energy of the local energy grid). Accordingly, different energy distribution and raw material acquisition profiles and levels have been also obtained (see Fig. 15 and Fig. 16, respectively). In order to better observe the differences between the non-coordinated and coordinated scenarios, the reader can compare Figs. [5 – 10] vs. Figs. [11 – 16].

Fig. 14. Energy plants production levels (coordinated system)

Fig. 15. Energy distribution plan (coordinated system). *mk_e4* and *mk_e5* correspond to external markets

Fig. 16. Acquisition of EGSC raw material (coordinated system)

In order to emphasize the changes between the coordinated and non-coordinated scenarios, Fig. 17 shows the detailed changes in the production orders. As it can be observed, the most profitable production/distribution levels to attend the market demands were dominated by the polystyrene plants *pl_s2* and *pl_s3*. Polystyrene plant 1 (*pl_s1*) starts to produce when the market demand is too high and the other plants are overloaded. As the non-coordinated decision making disregards the effect of the operation of the EGSC in order to minimize its total cost, such solution adds more pressure on the energy plants leading to high EGSC total cost. In the coordinated scenario, the planning strategy is different: the decision making system takes into consideration the EGSC operation/distribution concerns to improve the solution of the overall SC. Since the combustion energy plants are the most profitable ones, the polystyrene production (market demand for the EGSC) is being distributed among all polystyrene plants to exploit all the combustion plants , while in the non-coordinated scenario, the combustion technology has been unexploited. Additionally, gasification plants are functioning to avoid the use of the local network (the most expensive choice).

Fig. 17. Distribution of polystyrene production

4.3 Economic analysis

In the “coordinated” scenario, all information of both SCs (costs and constraints) has been included into the problem model. The optimal solution corresponds to produce polystyrene using most of the energy available from the local/cheaper energy generation plants (within their capacity constraints). The economic results reveal that the coordination between the PDSC and the EGSC improves the “entire SC” total cost with 2.46%, with a total savings *434,169 €* during the considered 10 time periods horizon (Table 6).

As it can be observed from Fig. 18, the coordinated SCs behave in favor of the most profitable performance of the entire SC. They both coordinate together to achieve the coordinated entire SC main objective. The transport (and inventory) costs of the PDSC increase by *44,813 €* (and *82 €*, respectively) but, simultaneously, the EGSC improves the savings of: *34,356 €; 1,584 €; 442,973 €* in the raw material purchases, transport, and energy production total cost, respectively. The coordinated PDSC total cost is slightly higher than the case of non-coordinated, but with such a slight increase a high decrease in the EGSC cost can be achieved, in favor of the coordinated scenario. Consequently, a clear tradeoff can be seen among the decisions of the SCs under study.

Finally, in addition to the savings in the total costs, the coordinated management shows higher incomes than the non-coordinated management for the presented case study.

Fig. 18. Detailed costs distribution

Table 6. Economic analysis

During the analysis of these and other comparative results (i.e.: from other SC structures and economic scenarios), three main parameters have been confirmed as the most significant: (i) the intermediate resources production rates (energy, in this case study) determine the coordination strategy between SCs. (ii) Lower suppliers' capacity and lower inventory limits are usually required after coordination. (iii) Global SC expansion offer new opportunities to better exploit/compensate eventual changes in the efficiency/productivity of some echelons (e.g.: in the presented case study, a lower energy generation cost will make profitable to sell the energy produced in the EGSC to the local electrical grid and, in turn, to buy energy from this local grid to satisfy the PDSC requirements).

5. Conclusions

The integrated decision-making perspective proposed in this work has been described and studied in order to advance towards a "Coordinated Supply Chain Management" paradigm. The presented generic model allows considering the SC echelons to be flexibly linked together, to build a SC network whose limits may be adjusted according to the capacity of the management to readily coordinate the resultant structure and to integrate the objectives of all echelons SC's within one final objective function. The emerging planning model is then useful to analyze the behavior of these SCs as a function of this resultant structure which, when coordinated among one single SC, is found to be different than when studied separately. Such a behavior affects the planning decision orders since the coordinated planning model is able to find a more globally profitable decision-making.

All these elements are included in the provided LP model, which is intended to solve and optimize any generic multi-echelon SC planning problems. Further to the simplistic proportional factors used to expose its basic formulation and to illustrate the proposed case study, the SC structure is able to include inner SC details, the main characteristics of each echelon/organization may be considered and coordinated while optimizing the total cost of the global resulting SC, and the different specific working details of each echelon may be easily incorporated to the system.

The resulting model is flexible enough to allow a coordinated management of the production, storage, and distribution tasks and thus helps in improving the global goal of the new "coordinated" SC. All involved organizations are affected by the final decisions and thus the new approach gives them the opportunity to share responsibilities. Furthermore, the application of this model to a problem involving decision making under uncertainty in the external scenario behavior and/or in the forecast of the relations between the considered variables (e.g. negotiation limits among echelons of different SCs), to the analysis of cooperative vs. competitive scenarios, and to consider multiple objective analysis to include local objectives of individual SCs, is straightforward.

The system has been proved by its application to a case study based on a pilot plant scale SC (biomass acquisition, energy generation, production–distribution organization, and waste treatment). The coordinated results show to be promising since, besides the reduction of the total cost, a better use of resources is achieved and less raw materials (biomass) are required to meet the same market requirements.

The coordinated management adds to the PSE science a new point of view to consider the detailed information of all enterprises sharing the system network, and therefore the opportunity to find improved and more comprehensive use of natural, productive, information and management resources.

Nomenclature

Indexes

e	*echelon (distribution center, market, production plant,…)*
r	*consumable resource (raw material, product, energy, steam, cash…)*
s	*supply chain*
t	*time period*

Sets

E	*echelons (distribution centers, markets, production plants,…)*
M	*external markets (final consumers)*
M_s	*external markets for SC s*
N	*raw material suppliers*
N_s	*raw material suppliers for SC s*
R	*consumable resources (raw materials, products, steam,…)*
S	*supply chains*
T	*time periods*

Parameters:

$dis_{e,e'}$	*distance between echelon e and echelon e'*
$dmd_{r,e,t}$	*external demand of resource r in echelon e (final consumer) at time t*
$prd^{max}_{r,e,t}$	*maximum delivering capacity of resource r at echelon e (plant/supplier) at time t*
$prd^{min}_{r,e,t}$	*minimum delivering capacity for resource r at echelon e (plant/supplier) at time t*
$prf_{r,r',e}$	*production factor: quantity of resource r required to produce resource r' in echelon e*
$st0_{r,e}$	*initial storage level of resource r in echelon e*
$sto^{max}_{r,e,t}$	*maximum storage capacity in echelon e for resource r at time t*
$sto^{min}_{r,e,t}$	*maximum storage capacity (safety stock) in echelon e for resource r at time t*
$val_{r,e,t}$	*unitary cost value of resource r at echelon e, time t*
$vpr_{r,e,t}$	*unitary production cost value to produce resource r from its raw materials at echelon e, time t*
$vpy_{r,e,t}$	*unitary penalty cost for extra-delivery of resource r at echelon e (market) at time t*

$vst_{r,e,t}$	*unitary storage cost of resource r at echelon e at time t*
$vtr_{r,e,e'}$	*unitary transport cost for resource r from echelon e to echelon e'*

Variables:

COS	*total cost*
CPR_t	*production cost*
CRM_t	*cost of the externally supplied resources*
CST_t	*storage cost*
CTR_t	*transport cost*
$DLV_{r,e,e',t}$	*amount of resource r delivered from echelon e to echelon e' at time t*
PFT	*aggregated profit of the entire system*
$PRD_{r,e,t}$	*production levels of resource r in echelon (plant) e at time t*
SAL	*economic incomes (sales value)*
$STO_{r,e,t}$	*storage level of resource r in echelon e (or its associated warehouse) at time t*

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Appendix A

The proposed coordinated model has been implemented to a multi echelon multi-site multi-product case study. Accordingly, the parameters that characterize the SC performance are provided below (raw materials and product prices; distribution data; production, inventory, distribution, suppliers limits; and final products demands)

Table A1. Polystyrene RM purchase prices

Table A2. Distance between polystyrene production plants and distribution centers

Table A3. Distance between polystyrene distribution centers and markets

Table A4. Maximum storage capacity

Table A5. Maximum production capacity

Table A6. Maximum supplier capacity

Table A7. Polystyrene production cost and energy requirements

Table A8. Polystyrene retailed price

The Energy production plants are based on gasification or combustion technology, separately. Gasification is a process that turns through a high-temperature partial oxidation of carbonaceous materials to produce syngas, mainly carbon monoxide and hydrogen (ThyssenKrupp Uhde®, 2012). The syngas then passes through different treatment steps ended up with a turbine to generate electricity. Various processes technologies are used to produce this syngas flow: the fixed-bed gasification, the fluidized-bed gasification, and the entrained flow gasification (Obernberger and Thek, 2008). The characterization of the gasification plants used in the case study (*pl_e1, pl_e2, pl_e3*) are based on typical figures of a downdraft fixed bed gasifier of *5 MWe* nominal capacity.

On the other hand, combustion consists on the complete oxidation of fuel at high temperatures. The hot gases resulted from the combustion process can be used for heating purposes or conducted to a generator to produce electricity (Lackner *et al.*, 2010). Several technologies can be also used for energy production based on biomass combustion: the steam turbine process, the steam piston engine process, the steam screw-type engine process, the Organic Rankine Cycle (ORC) process, and the Stirling engine process (Obernberger and Thek, 2008). In all cases, the main equipment units include RM mixing, air supply, heat transfer, exhaust gas cleaning, and a system to discharge combustion residues. Typical numbers associated to steam turbine combustion plants of max production capacity *5 MWe* are used for all combustion plants (*pl_e4, pl_e5, pl_e6*) included in the presented case study. The minimum production capacities in both gasification and combustion plants have been all assumed to be *0 kWh* (the eventual minimum load requirement has been neglected), and no constraints in the detailed working schedule have been considered so any energy requirement associated to a production site between *0 MWh* to *3000 MWh* (*2 plants x 5 MW x 300 h*) is considered feasible (tactical point of view).