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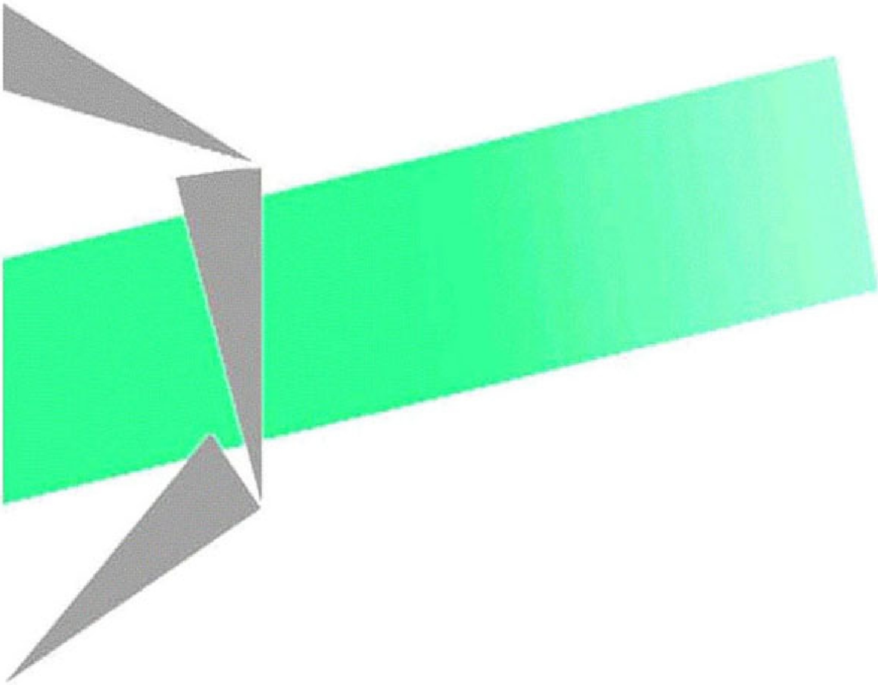

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Maxime Ogier, Van-Dat Cung, Julien Boissière

Laboratoire G-SCOP
46 av. Félix Viallet, 38000 GRENOBLE, France
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Maxime Ogier[1], Van-Dat Cung[1], Julien Boissire[2]
[1] Grenoble-INP / UJF-Grenoble 1 / CNRS (G-SCOP UMR5272)
46 Avenue Flix Viallet, 38031, Grenoble (France)
{maxime.ogier,van-dat.cung}@grenoble-inp.fr
[2] Universit de Savoie (LISTIC EA3703)
74016, Annecy (France)
julien.boissiere@univ-savoie.fr

Abstract : *Supply chain optimization is a very complex task when taking into account its inherently decentralized aspect and sustainable development considerations. In order to provide a sustainable supply chain model faithful to reality, this paper presents a two actors supply chain model with a manufacturer and a 3PL provider. Centralized and decentralized planning at tactical level, with lot-sizing models, presented by Jung et al. (2008) is studied. This model is extended by including rolling planning horizon, and demand forecast errors, to take into account difficulties of supply chain actors to evaluate future demands. A preliminary experimental study highlights the good economic performance of the decentralized planning and the consequences of demand uncertainty on supply chain total cost. Then, we point out the poor production resource management with rolling horizon planning. Because of social consequences that may result, a new constraint is integrated in the supply chain model : securing production resources. This results in the impossibility to modify the planning on the coming periods. The economic impact of the integration of this social criteria is studied. Results are presented based on deterministic or stochastic demands, and with different rolling horizon length. It points out that securing production resource is not very expensive when planning on a small rolling horizon or with deterministic demands. Various future extensions of this model are also discussed.*

Keywords : *Sustainable Supply Chain, Decentralized planning, Rolling planning horizon, Advanced lot-sizing*

1 Introduction

Supply chain management is a key consideration in the development of sustainable industrial world (Linton et al., 2007). This area has become interesting for both researchers and industries themselves. Indeed, supply chain are composed of different actors (independent decision-maker entities), and optimizing independently each actor does not give very good overall results. Thus, either for strategic level decisions such as supply chain design or at tactical level for supply chain planning, it is preferable to consider the supply chain as a whole. Furthermore, under the pressure of customers and governments, the idea emerges that companies should no longer just aim for the economic criterion alone, but incorporate environmental and social aspects (Seuring and Müller, 2008). New sustainability criteria make more complex model, and it reinforces the idea of global supply chain. Our interest is on planning optimization at tactical level with integration of a sustainable criterion.

Works have been carried out to study the problem with a centralized supply chain and have provided very good results (Park, 2005). However, it is difficult to meet these results in an industrial world context because of two major reasons. First, companies belonging to the same supply chain are reluctant to share confidential data (capacities, costs, prices) with other actors, who can sometimes be partnered with their competitors. Secondly, centralized problems can be modeled as lot-sizing problems (Drexl and Kimms, 1997), and are often difficult to solve because of their computational complexity, and their large size involves a huge solving time (Almeder, 2010). Thus, the alternative to this centralized approach is to consider global supply chain as decentralized. This raises the question of coordination mechanisms between actors in order to get results as close as possible to those of the centralized approach. These mechanisms require information sharing between actors. Besides, note that in an industrial world context as little information as possible should be exchange, and if possible information with a low degree of confidentiality.

In this paper, as a first step to compare centralized versus decentralized approaches, we study a 2-echelon supply chain at the tactical level optimizing the production and distribution planning based on clients demands. This planning is at tactical level and is equivalent to a Master Production Scheduling (MPS). Hence operational management like inventory management is not considered. The actors, a manufacturer in charge of the production and a logistician in charge of final goods transport and inventory, need to regularly plan their respective quantities on a rolling planning horizon. In the decentralized case, a negotiation process with minimal information sharing from Jung et al. (2008) permits to coordinate the two actors. We then point out late and sudden changes in the planned production quantities when planning on rolling horizon. Hence we introduce a sustainable aspect which is securing production resources. It consists in better anticipating the use of these resources, by adjusting production quantities during planning using frozen, slushy and liquid periods. Impacts on the performance of centralized and decentralized supply chains are then studied.

This paper is organized as follows. Section 2 presents a review of the literature. Section 3 describes Jung et al.'s model and first results with rolling horizon. The sustainable criterion is presented and introduced in the planning model in Section 4. Experimental results and economic consequences of securing production resources are then presented in Section 5. A conclusion and research prospects are drawn in Section 6.

2 Literature review

In the existing literature, a great number of articles deal with centralized and decentralized supply chain. A lot of reasons explain the importance of coordination in the supply chain. All the actors do not share the same goals, the same performance metrics and do not face the same problems (spatial repartition, lot sizing, ...). Moreover, if they do not know the demand of the downstream echelon, they have to forecast it, and they often tend to forecast more than the real demand, causing the well-known bullwhip effect. More details can be found in Cachon and Lariviere (2001) and Arshinder et al. (2008).

Thus, on a fixed planning horizon, a centralized supply chain permits to lower the total cost (Park, 2005) since all the information are known. But some drawbacks of centralized supply chain are pointed out. Giannoccaro and Pontrandolfo (2004) explain centralized control gives very good results but does not seem very realistic. Indeed, a single coordinator-decision maker would be necessary, and he would know the whole information of the companies belonging to the supply chain. Jung et al. (2008) highlight two companies could want the minimum information sharing because they do not totally trust each other, and some private data must not be shared. Our interest lies in decentralized supply chain which is a more realistic model.

In order to reach a good overall performance in a decentralized supply chain, actors should coordinate. It is then necessary to choose the shared information and a coordination mechanism. An interesting literature revue dealing with information sharing is proposed in Huang et al. (2003). Chen (2003) and Arshinder et al. (2008) give more examples. Moreover, coordination mechanisms have been extensively studied in the literature and can achieve the same result than with a centralized supply chain. Their advantage is to coordinate a decentralized supply chain increasing its performances. According to Cachon (2003), "a *contract* is said to *coordinate* the supply chain if the set of supply chain optimal actions is a Nash equilibrium, i.e. no firm has a profitable unilateral deviation from the set of supply chain optimal actions". Some classical contracts are the quantity-flexibility contracts (Tsay, 1999), the revenue-sharing contracts (Cachon and Lariviere, 2005), the quantity discount contracts (Weng, 1995). A good literature revue can be found in Giannoccaro and Pontrandolfo (2004) and Cachon (2003). These classical coordination mechanisms with contracts consider supply chain model with a supplier and a retailer in the newsvendor model, with some extensions (Cachon, 2003): this is a single-period model, and to optimally parameter the contracts, confidential informations of the two actors are required but difficult to obtain. Jung et al. (2008) study a decentralized lot-sizing problem. They propose a negotiation process for a multi-period planning with fixed horizon, which also has the advantage to share only one information: the demand quantities the two actors are willing to exchange. This permit to coordinate the two decentralized lot-sizing problems. Notice that there is no supply chain coordination within the meaning of Cachon (2003) since there is no guarantee on the sharing of the costs for each actor when accepting the negotiation process. In this paper Jung et al.'s negotiation process is used because it is considered quite realistic, and have given rather good results.

It is clear that to simulate planning at tactical level in a supply chain, decentralized version is more realistic. But for realistic planning an important literature also deal with rolling planning horizon. The most studied problem is the multilevel lot-sizing problem in a rolling horizon environment. Some works can be found in Blackburn and Millen (1980), Baker (1977), Sridharan et al. (1987). More recent works try to find better heuristics for rolling horizon (Stadtler, 2000; Van Den Heuvel and Wagelmans, 2005), for example trying to "see beyond the planning horizon". Indeed, exact algorithms in the fixed horizon case are heuristics in the rolling horizon case. So it can be interesting to find better heuristics (Stadtler, 2000). Indeed, some properties in the fixed horizon case are no longer true in the rolling horizon case, for example the final zero inventory level. It is cost-optimal in a fixed horizon planning to have no inventory at the end of the horizon, but in the rolling planning horizon an ending inventory is needed. This is called the truncated horizon effect (Federgruen and Tzur, 1994). Hence, in this paper, planning is done on a rolling horizon basis. The heuristic chosen is an exact lot-sizing with a specified ending inventory.

Furthermore industrial planning with rolling horizon is of great interest in the literature. Because of demand uncertainty Master Production Scheduling (MPS) at tactical level frequently changes and this can induce major change in the Material Requirements Planning (MRP) at operational level (Xie et al., 2004; Zhao and Lam, 1997; Yeung et al., 1998). Our study is a planning equivalent to MPS since it is at tactical level and products are aggregated per family. These late and frequent change at tactical level should be avoided because induced changes in the MRP can have economical, environmental and social overcosts. To avoid this, some periods of the planning horizon are frozen that is to say decisions on those periods can no longer be changed. The other periods of the planning horizon can be free, or sometimes after the frozen horizon there is a slushy horizon in which decisions can change but in a restricted interval. In this case the remaining horizon is called the liquid horizon. These terms are mentioned in Berry et al. (1979). Besides, numerous works deal with the determination of the parameters affecting the MRP performance, such as the number of frozen periods and the frequency of replanning (Zhao and Lam, 1997; Sridharan et al., 1987). These aspects are not studied in this work.

Furthermore, there is a more recent literature on supply chain management dealing with sustainable supply chain. This idea is of great interest because sustainable development consists in using resources to satisfy present needs without compromising future generations' ability to meet their own needs (Linton et al., 2007). Researches and operational research tools can be useful for sustainable supply chain management (Linton et al., 2007; White and Lee, 2009). Two interesting literature review can be found in Seuring and Müller (2008) and in Srivastava (2007). Nevertheless, sustainable development is often reduced to environmental improvement (Seuring and Müller, 2008). Moreover Benjaafar et al. (2010) and Seuring and Müller (2008) point out that cooperation and information sharing between actors is necessary to promote a sustainable supply chain.

To our knowledge, there has been no significant research on the integration of social aspects when planning in a global supply chain. Moreover, in order to integrate industrial considerations, the supply chain model considered should be decentralized with coordination between actors, and planning should be done on a rolling horizon basis.

3 Jung et al.'s model revisited with rolling horizon

In this paper our interest is focused, without loss of generality, on a 2-echelon supply chain with one actor at each echelon. A centralized and a decentralized version of this supply chain are studied, based on those presented by Jung et al. (2008). The study is at tactical level. Indeed, the two actors of the supply chain plan production, transportation and inventory for a single product. In order to be closer to industrial reality this planning is done on a rolling planning horizon basis. Moreover two different knowledge of the demand are considered. On the one hand a deterministic case where demand is perfectly known on the rolling planning horizon, on the other hand a stochastic case where accuracy of the forecasted demand decreases with temporal distance.

This basic supply chain template permits:

- to have a model not so far from the reality,
- to easily analyse and understand how the two-actor negotiation process evolves and converges on a planning in the decentralized version,
- to compare the decentralized and centralized versions,
- to study the impact of an inaccurate knowledge of demands.

This work is inspired from the one presented by Jung et al. (2008).

3.1 The model

3.1.1 A MIP formulation

The original model from Jung et al. (2008) presented in Figure 1 considers a supply chain with two actors: the manufacturer actor (MA) and the logistician actor (LA) who is a 3PL logistics provider. For the sake of simplicity and his detailed interpretation (without loss of generality), the model presented here consider one product, one production facility, one distribution center and one customer zone. This permits to better observe what occurs in the model, such as the convergence of the negotiation process and the financial impacts for each actor. A more general model is presented in Jung et al. (2008) or Ogier et al. (2010). MA manages the production facility (production and storage) and LA manages the distribution center (transportation from the production facility to the distribution center, storage). The aim is to coordinate the two actors for a good global performance of the supply chain. Coordination is achieved when the deliverable quantities produced by the manufacturer in each period are equal to the quantities required and carried by the 3PL logistics provider. In the decentralized case, the bi-directional information they share are only the quantities required transmitted by LA to MA and the quantities available transmitted by MA to LA. In the negotiation process, each actor optimizes its production plan using a capacitated single-item lot-sizing model, formulated as a MIP (Mixed Integer Programming), by taking into account the information received.

The parameters are as follows:
T = set of periods,
D_t = demand at period $t (\in T)$,
r_t = unit production cost at period t,

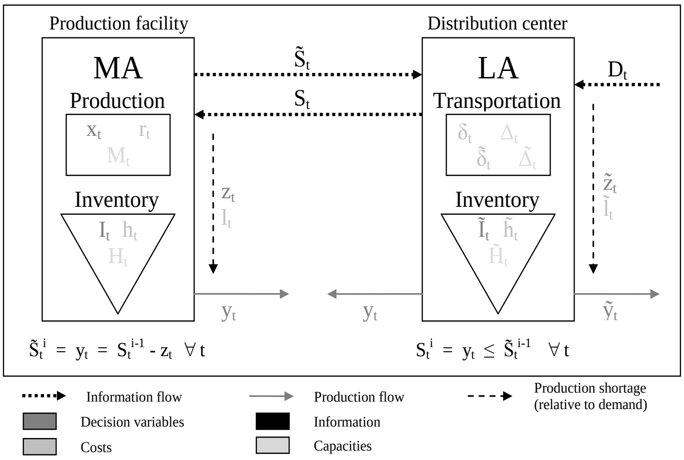

FIG. 1: The 2-echelon supply chain model.

δ_t = unit transportation cost from production facility to distribution center at period t,
$\tilde{\delta}_t$ = unit transportation cost from distribution center to customer zone at period t,
h_t = unit inventory holding cost in production facility at period t,
$\tilde{h}_t$ = unit inventory holding cost in distribution center at period t,
$\tilde{l}_t$ = unit lost sales penalty cost in distribution center at period t,
H_t = storage capacity in production facility at period t,
$\tilde{H}_t$ = storage capacity in distribution center at period t,
M_t = production capacity in production facility at period t,
Δ_t = transportation capacity from production facility to distribution center at period t,
$\tilde{\Delta}_t$ = transportation capacity from distribution center to customer zone at period t.

The decision variables are the followings:
x_t = production quantity at period t,
y_t = transportation quantity from production facility to distribution center at period t,
$\tilde{y}_t$ = transportation quantity from distribution center to customer zone at period t,
$\tilde{z}_t$ = lost sales quantity in customer zone at period t,
I_t = inventory level in production facility at period t,
$\tilde{I}_t$ = inventory level in distribution center at period t.

As presented in Jung et al. (2008) the optimization problem for the centralized supply chain planning (CSCP) is given as follows:

$$Min \sum_{t \in T} \left(r_t \cdot x_t + h_t \cdot I_t + \delta_t \cdot y_t + \tilde{\delta}_t \cdot \tilde{y}_t + \tilde{h}_t \cdot \tilde{I}_t + \tilde{l}_t \cdot \tilde{z}_t \right) \tag{1}$$

Subject to

$$I_t = I_{t-1} + x_t - y_t \qquad \forall t \tag{2}$$

$$\tilde{I}_t = \tilde{I}_{t-1} + y_t - \tilde{y}_t \qquad \forall t \tag{3}$$

$$\tilde{y}_t = D_t - \tilde{z}_t \qquad \forall t \tag{4}$$

$$x_t \leq M_t \qquad \forall t \tag{5}$$

$$I_t \leq H_t \qquad \forall t \tag{6}$$

$$\tilde{I}_t \leq \tilde{H}_t \qquad \forall t \tag{7}$$

$$y_t \leq \Delta_t \qquad \forall t \tag{8}$$

$$\tilde{y}_t \leq \tilde{\Delta}_t \qquad \forall t \tag{9}$$

$$x_t, I_t, \tilde{I}_t, y_t, \tilde{y}_t, \tilde{z}_t \in \mathbb{N} \qquad \forall t \tag{10}$$

Basically, the objective function (1) seeks to minimize the total costs of the supply chain, constraints (2) - (4) ensure the commodity flow conservation, constraints (5) - (9) are capacity restrictions and (10) are the decision variables' constraints.

In the decentralized case, for the agent-based decentralized supply chain planning (AD-SCP)[1], there are two optimization problems coming from the previous centralized case. For MA, new parameters and decision variables are defined as follows:

Parameters:
l_t = unit production shortage penalty cost in production facility at period t,
S_t = the requested supply quantity in production facility at period t.
Decision variables:
z_t = production shortage quantity in production facility at period t.

The production planning problem for MA is formulated as follows:

$$Min \sum_{t \in T} (r_t \cdot x_t + h_t \cdot I_t + l_t \cdot z_t) \tag{11}$$

Subject to

$$I_t = I_{t-1} + x_t - y_t \qquad \forall t \tag{12}$$

$$y_t = S_t - z_t \qquad \forall t \tag{13}$$

$$x_t \leq M_t \qquad \forall t \tag{14}$$

$$I_t \leq H_t \qquad \forall t \tag{15}$$

$$x_t, I_t, y_t, z_t \in \mathbb{N} \qquad \forall t \tag{16}$$

The objective function (11) seeks to minimize the costs of MA. Constraints (12) ensure commodity flow conservation for the production. Constraints (13) result from the negotiation process. Constraints (14) and (15) are capacity restrictions, and (16) are constraints on the decision variables.

For LA, there is one new parameter:
$\tilde{S}_t$ = the available supply quantity in production facility at period t.

And the logistics planning problem for LA is as follows:

$$Min \sum_{t \in T} \left(\delta_t \cdot y_t + \tilde{\delta}_t \cdot \tilde{y}_t + \tilde{h}_t \cdot \tilde{I}_t + \tilde{l}_t \cdot \tilde{z}_t \right) \tag{17}$$

Subject to

$$y_t \leq \tilde{S}_t \qquad \forall t \tag{18}$$

$$\tilde{I}_t = \tilde{I}_{t-1} + y_t - \tilde{y}_t \qquad \forall t \tag{19}$$

$$\tilde{y}_t = D_t - \tilde{z}_t \qquad \forall t \tag{20}$$

$$\tilde{I}_t \leq \tilde{H}_t \qquad \forall t \tag{21}$$

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[1] Jung et al.'s terminology. In this paper, an actor is considered as an agent.

$$y_t \leq \Delta_t \qquad \forall t \tag{22}$$

$$\tilde{y_t} \leq \tilde{\Delta}_t \qquad \forall t \tag{23}$$

$$\tilde{I}_t, y_t, \tilde{y_t}, \tilde{z}_t \in \mathbb{N} \qquad \forall t \tag{24}$$

The objective function (17) seeks to minimize the costs of LA. Constraints (18) result from the negotiation process. Constraints (19) and (20) ensure commodity flow conservation for the production. Constraints (21) - (23) are capacity restrictions, and (24) are constraints on the decision variables.

Notice that MA and LA are linked by constraints (13) and (18) with respectively the variables S_t and $\tilde{S_t}$.

3.1.2 The negotiation process

The two actors in this supply chain must negotiate to reach an agreement on a joint planning. It is necessary that at the end, the quantities available at the production facility (y_t in MA's planning) and the quantities transported by LA (y_t in LA's planning) are equal. They exchange pieces of information that are the quantities they plan to carry (S_t) or they plan to ship ($\tilde{S_t}$). Everyone considers this information in order not to provide more than what the other is willing to ship/transport. Equations (13) and (18) ensure this constraint.

LA starts the process by optimizing its planning according to the customer demand. MA tries to satisfy as much as possible the forecast quantities of LA: there is a per-unit cost l_t to pay if MA provides a quantity less than that requested by LA. The process stops when LA and MA agree on the quantities, thus MA does not pay a penalty at the end of the process.

It should be noticed that this negotiation process never allows actors to increase forecast quantities. The fact of lowering the quantities during the negotiation process makes possible to demonstrate the convergence of the process (Jung et al., 2008). Moreover, this process advantages LA because it starts the negotiation. This can be justified if we consider that commodity flows are pulled by demand.

3.1.3 Demand forecast

For each planning the logistician knows customers' demands only on a small number of periods. Two cases are considered. First, the deterministic case where all demands are certain and from one planning to the next, there is only one new demand (that of the last period of the new planning). Secondly, the stochastic case where demands are no longer certain. Demand for the initial planning period is known with certainty, and then there is an uncertainty for the other periods that increases as shown in Table 1. An uncertainty of 2.5% means that demand is estimated at ±2.5% of the real demand.

Period	$t+0$	t+1	$t+2$	$t+3$	$t+4$	$t+5$	$t+6$	$t+7$	$t+8$ and more
Uncertainty	0%	2.5%	5%	7.5%	10%	15%	20%	30%	40%

TAB. 1: Evolution of uncertainty depending on the period.

3.2 Results with rolling horizon

3.2.1 Instance structures

Instances are selected from those presented in Jung et al. (2008). But in this paper a simplified version of the model is considered with a single product, a single production facility, a central distribution center and one final customer. $U(a, b)$ means the uniform distribution between the values a and b. The instance structures for demand and unit costs on which our tests are based are presented in Table 2.

Demand		$D_t = U(1500;3500)$
Unit costs	Production	$r_t = c_t + d_t$ $c_t = U(45;55) d_t = U(0;5)$
	Holding (MA)	$h_t = \frac{1}{2} \cdot r_t \cdot U(0.9;1.1)$
	Transport MA → LA	$\delta_t = \frac{1}{4} \cdot r_t \cdot U(0.9;1.1)$
	Holding (LA)	$\tilde{h}_t = \frac{1}{2} \cdot r_t \cdot U(0.9;1.1)$
	Transport LA → Customer	$\tilde{\delta}_t = \frac{1}{4} \cdot r_t \cdot U(0.9;1.1)$
	Lost sales penalties	$l_t = \tilde{l}_t = 10000$

TAB. 2: The instance structures.

With these instance structures, demand is fairly fluctuating (±40%). Let us recall that 40% is the maximum uncertainty in demand.

The holding cost for MA represents half of the production cost. So, it is always more interesting to produce just in time, if the capacities allow it. For LA, transportation cost from MA to the customer and holding cost for one period is equivalent to the production cost for MA. For LA, the transportation cost from MA to the customers ($\delta_t + \tilde{\delta}_t$) is equivalent to the holding cost ($\tilde{h}_t$). Hence, for LA, it is always more interesting to transport products between the factory and the customer just in time. Lost sales have a cost much higher than other costs, which encourages LA and MA to avoid lost sales. Remember that at the end of the negotiation process, MA has no penalties to pay because the quantities required by LA are satisfied. LA supports shortage penalties on its own, and it is considered that losing a sale is serious and so shortage penalties are expensive. Thus, its costs can increase dramatically in case of lost sales.

Concerning production, transport and storage capacities, values presented in Jung et al. (2008) are modified. In the model presented by Jung et al. (2008) the perspective was clearly deterministic. Capacities at a period t were chosen uniformly around the demand of period t. Therefore variability in capacity compared to demand was simulated.

In a perspective where demand is stochastic, it is less conceivable to generate capacities based on demands. Indeed, this may mean that capacities are related to the demand forecast and evolve according to the forecast. However, capacities considered here are tactical capacities well identified before planning and formerly defined. Moreover capacities can be chosen close to the real demand, but in this case capacities guide the solution because even if demand forecasts are wrong, capacities keep close from real demand. In this paper three cases are considered in order to generate tactical capacities for production, storage and transport from the factory to the distribution center:

- Fixed 120%: capacities are constant over all periods and equal to 120% of average demand. In this case there are no distinction between periods and the supply chain is in overcapacity.

- Fixed 100%: capacities are constant over all periods and equal to 100% of average demand. This case means that there are no distinctions between periods and capacities are average adapted.

- Variable: capacities vary uniformly between 80% and 120% of average demand. This case means that capacities change randomly from one period to the next. There may be some periods with more or less working days, or maintenance of certain machines was planned. On average, capacities are set to meet demand. However it should be noted that there is another difficulty compared to the two previous cases. In one period different capacities are no longer equal, that is to say that production can be in overcapacity and transport in undercapacity in the same period.

Moreover, regarding the transport capacities between the distribution center and the customer, it is assumed that the customer can always be delivered. Otherwise lost sales would be generated automatically. Hence, in all three cases, the transport capacities between the distribution center and the customer at period t are set equal to the demand at period t. For the three cases, the structure of the capacities in the instance are presented in Table 3. $\bar{D}$ represents average demand. Here the average demand is 2500, so in the first case, capacities (except transport from LA to the customer) are fixed to 3000. Demand varies uniformly between 1500 and 3500, so it is possible in some periods to have production or transport undercapacity and therefore it is not possible to produce just in time on the entire horizon length. In the second case capacities are fixed to 2500. Thus, there are more periods with production or transport undercapacity, and therefore it is very important to anticipate and to make a good use of overcapacity periods. In the third case, each capacity varies uniformly between 2000 and 3000. In this case anticipation is even more important, given that over the same period the various capacities are not equal.

Capacity case	Fixed 120%	Fixed 100%	Variable
Production (M_t)	$1.2 \cdot \bar{D}$	$\bar{D}$	$U(0.8; 1.2) \cdot \bar{D}$
Storage MA (H_t)	$1.2 \cdot \bar{D}$	$\bar{D}$	$U(0.8; 1.2) \cdot \bar{D}$
Transport MA → LA (Δ_{fdt})	$1.2 \cdot \bar{D}$	$\bar{D}$	$U(0.8; 1.2) \cdot \bar{D}$
Storage LA ($\tilde{H}_t$)	$1.2 \cdot \bar{D}$	$\bar{D}$	$U(0.8; 1.2) \cdot \bar{D}$
Transport LA → customer (Δ_{dct})	D_t	D_t	D_t

TAB. 3: The structure of the capacities in the instance.

Unlike Jung et al. (2008), we consider the planning is done on a rolling horizon basis. The length of the whole planning horizon is the total number of periods considered. The length of the rolling horizon is the number of periods considered for each planning. So for each period of the whole planning horizon, a planning is done on the rolling horizon. For planning with a rolling horizon, it is better to specify an inventory level for the last period avoiding to start with an empty inventory for the next period (Ogier et al., 2010). Here, this inventory level is adapted to the demand and its fluctuations. The final inventory is considered according to the average of the demand on the rolling planning horizon. It is set equal to 45% of the average demand. However, the maximum storage capacity should be respected (if the demand average is too important). This inventory is set to a level which is expected to achieve the continuity of the service and the satisfaction of the demand. Indeed, a planning is done on a small number of periods, and it ignores what may happen afterwards.

The models are developed in Java and for the MIP the interface Concert Technology is used to run with CPLEX 12.2.

3.2.2 Two major results : how to plan ? how to anticipate ?

The following results are presented using these three categories of tactical capacities. Figures relative to uniform capacities are present in Appendix A. This section discusses the effect of the rolling horizon on the total cost of the supply chain. The supply chain in its centralized (CSCP) and decentralized (ADSCP) version are studied along with the deterministic and stochastic demand cases and the rolling planning horizon. Figure 2 presents the total cost depending on the rolling horizon length in the case of variable capacities. Results with the constant capacities case are presented in Figures A.1 and A.2. For the three capacities cases, the shapes of the curves are similar.

Let us set RHL_{det} and RHL_{sto} the rolling horizon length from which supply chain total cost is lower in the centralized case, respectively for deterministic (det) and stochastic (sto) demands. So far RHL_{det} or RHL_{sto} planning optimization in the decentralized supply chain permit to have a lower total cost. Let us set ${RHL_{CSCP}^{sto}}^*$ and ${RHL_{ADSCP}^{sto}}^*$ the rolling horizon

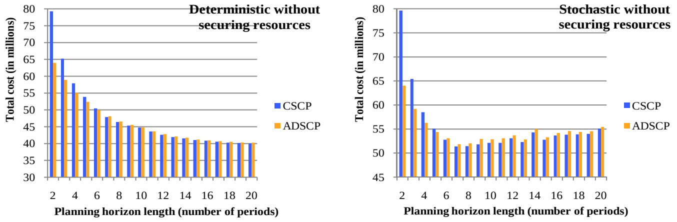

FIG. 2: Evolution of the total cost in deterministic and stochastic cases with variable capacities between 80% and 120% of average demands.

length for which total supply chain cost is the lowest, in the stochastic case, for respectively the centralized and decentralized supply chain. For each capacities case, Table 4 presents results concerning the rolling horizon length previously presented.

Case	RHL_{det}	RHL_{sto}	${RHL^{sto}_{CSCP}}^*$	${RHL^{sto}_{ADSCP}}^*$
Fixed 120%	4	4	4	3
Fixed 100%	12	7	17	17
Variable	7	6	7	7

TAB. 4: Comparison of the tree capacities cases : rolling horizon length from which cost is lower in the centralized case and for which cost is the lowest in the stochastic case.

As expected a first result is that if there are reliable data about demand, it is better to plan on the longest possible rolling horizon. Indeed, in the deterministic case, costs clearly decrease when the rolling horizon length increases.

However, if the demand forecast is not reliable, planning on a large number of periods is not very good because the further one plan, the worse it gets. Thus the length of rolling horizon which gives the lowest total cost is of great interest. For the variable capacities case, in the case of stochastic planning, the best results from our experiments are obtained for a 7 periods rolling planning horizon in the centralized and decentralized cases.

When planning on a small rolling horizon, it seems better to consider the decentralized version of the supply chain. This is true in the stochastic and deterministic cases. This result is remarkable because when computing a global planning on a fixed horizon the centralized case is always cheaper.

4 Integration of a sustainable criterion

4.1 Problem description

In the rolling planning horizon process presented before it is possible to fully change the decisions from one planning to the next. This has important implications for production resources. This section highlights the high production nervousness of the previous model, and then explains why securing production resources is an important aspect of sustainability.

4.1.1 Production nervousness

Theoretically the former model allows abrupt changes between the planned production quantities and the effective production quantities. Indeed only one period after a planning decision is really fixed for the production, another planning is done again without taking into account the decisions of the previous planning. The behaviour of the system, regarding the production nervousness, has been observed during the simulation of a planning. We have considered two aspects:

- differences between forecasted production in period t and completed production in period $t+1$,

- the number of planning for which changes have been made.

The mean of absolute differences between planned production quantities in period t and quantities really produced in period $t+1$ are presented in Figure 3 for the deterministic and the stochastic case in a decentralized supply chain, with variable capacities. Results for fixed capacities are presented in Appendix B (Figures B.1 and B.3). Means and error bars presented correspond to the mean minus standard deviation values lower than average and the average plus standard deviation values above average. Standard deviations are calculated for each instance, and the average standard deviation on the 50 instances is presented. Let us set $x_{t'}^{t}$ as planned production quantity for the period t' when planning at period t. Then let $\delta_t^{t-1} = \left| \frac{x_t^t - x_t^{t-1}}{x_t^{t-1}} \right|$ be the absolute difference between planning at period $t-1$ and completion at period t. Then for one instance n, the mean on the whole periods Δ_n is calculated as follows: $\Delta_n = \frac{1}{T-1} \sum_{t=1}^{T-1} \delta_t^{t-1}$, and then the mean on the N instances presented in Figure 3 is calculated as follows: $\Delta = \frac{1}{N} \sum_{n=0}^{N-1} \Delta_n$.

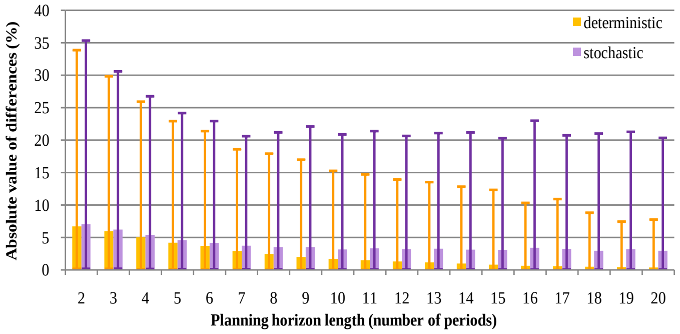

FIG. 3: The percentage differences between the forecast at a time t and the completion of production at period $t+1$ with variable capacities between 80% and 120% of average demands.

Figure 3 shows, as expected, that differences between forecasts and completions are less important in the deterministic case than in the stochastic case. Moreover, in the deterministic case absolute differences are decreasing when planning is on a larger rolling horizon. They are between 1% and 5%. However it should be noted that the standard deviations for values above average are quite significant, which means that the differences are very small for many planning but very important for some of them.

Let us introduce another indicator which is the number of planning for which the gap between forecast and completion is strictly positive. Let us recall the total number of periods is 50, so the total number of planning to compute is also 50 (because a rolling planning horizon is made). The results are presented for deterministic and stochastic case in Figure 4, for a decentralized supply chain, with variable capacities. Results for fixed capacities are presented in Appendix B (Figures B.2 and B.4).

Figure 4 highlights that there is a gap for some planning (about 10 out of 50). Thus, standard deviations presented in Figure 3 let us infer that when there is a gap it is quite large. Moreover, in the deterministic case, the number of changes decreases when planning on a larger rolling horizon, which explains that the average difference presented in Figure 3 also decreases. In the stochastic case, however, the number of changes does not diminish even when vision of the demand is on a larger rolling horizon. Thus, what can be earned having a long term vision is cancelled by a bad knowledge of demands. That is to say vision is farther but fuzzier.

Hence in the present model there is little change between forecasted and completed production quantities, but when there is a change it is a strong change. Then, it is obvious

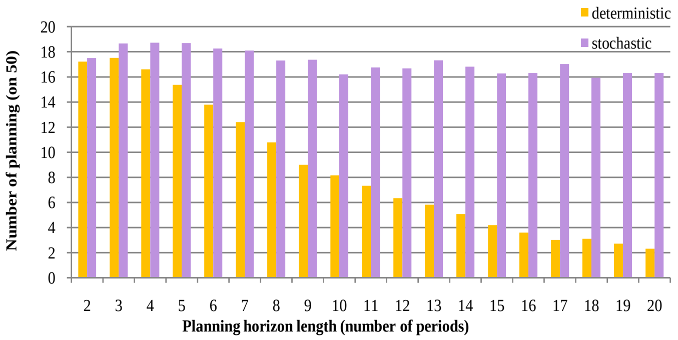

FIG. 4: Average number of planning for which there is a gap between forecast and completion with variable capacities between 80% and 120% of average demands.

that there is production nervousness in the supply chain, which has an impact on resource management.

4.1.2 A sustainable aspect: securing production resources

With the presented model, decisions can be reconsidered from one planning to the next. In this work, production quantities are more specifically studied. Changes just before production have two consequences. On the one hand, the number of hours may vary from the forecast made in period t and the completion in period $t + 1$. This can lead to poor management in terms of employment and working conditions for operators. Indeed, production planning are not stabilized, then it is possible to have sudden changes in the management of temporary workers and overtime. Secondly, changing production quantities means that orders to supplier may also change. Thus there is significant pressure on suppliers and there may be additional stocks to be managed either by the supplier, either directly in the manufacturing plant (which are not taken into account in the model).

The management of this social aspect is relevant to be integrated into the model. This can have both positive and negative consequences on economic and environmental criteria. Even if it does not appear in the model, late changes may incur costs because of an order cancellation, a late order, overtime, or lay-offs for some employees. Besides, securing production resources can have an impact on the energy bill as well because the use of production, transport and inventory resources evolves. However this environmental aspect is not discussed further here.

4.2 Changes in the model

Securing production resources results in changes in the model. Hereafter presents firstly how production resources are secured and secondly how the additional constraints are integrated into the model.

4.2.1 Division of the rolling planning horizon: Frozen, slushy and liquid periods

In order to secure production resources, an industrial approach is used. Frozen periods and slushy periods are introduced into the model. Initially, the rolling planning horizon is divided into three parts. The first is frozen, the second is slushy and the third is liquid. On the frozen periods, the quantities are fixed and cannot be modified during the planning; and on the slushy periods, the quantities may be modified but must remain within a given range (defined by a percentage, for example). On the liquid periods, changes can be made without restriction. Figure 5 shows the principle of this planning.

Let us consider the following parameters:

H = rolling planning horizon length in periods,
HF = number of frozen periods,

HS = number of slushy periods,
HL = number of liquid periods,
i = index of the first planning period.

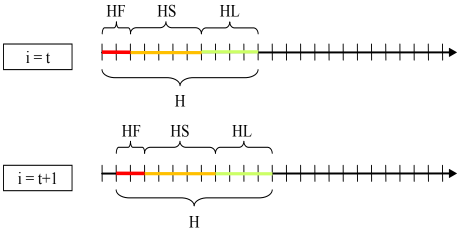

FIG. 5: A rolling planning over two periods with frozen, slushy and liquid periods.

4.2.2 New constraints in the MIP model

Concerning the supply chain model, some constraints of the MIP change. It should be noticed that secured resources are production resources only (not transportation, not inventory). Thus three new parameters are introduced:

x_t^{frozen} = production quantity defined at the previous planning on a frozen period,
x_t^{slushy} = production quantity defined at the previous planning on a slushy period,
α = flexibility percentage.

For frozen periods, all quantities are already fixed with the values determined in the previous planning, and new decisions are made only beyond the frozen periods. Thus, constraints on production variables are changed. More specifically, in the centralized model CSCP, and in the decentralized model ADSCP (for the manufacturer) two constraints on production variables are added:

$$x_t = x_t^{frozen} \qquad \forall t \in HF \tag{25}$$

$$(1-\alpha) \cdot x_t^{slushy} \leq x_t \leq (1+\alpha) \cdot x_t^{slushy} \qquad \forall t \in HS \tag{26}$$

Constraint 25 ensures the planned production quantities on the frozen periods (x_t) are equal to those planned in the previous planning (x_t^{frozen}). Constraint 26 ensures the planned production quantities on the slushy periods (x_t) are in an interval centered on the production quantity planed in the previous planning (x_t^{slushy}).

4.2.3 Feasible flow problem

The planning problem in a 2-echelon supply chain with single product and linear costs is a minimum cost flow problem. The new constraints involve that the minimum capacities on the flow are no longer all zero. Thus, before solving the minimum cost flow problem, we must ensure that there is a feasible flow.

In the decentralized case, before solving the problem, it is necessary to ensure that the flow of the manufacturer (MA) is feasible. The graph considered is presented in Figure 6. Each arc has a maximum and minimum capacity. A 6 periods length planning is considered here (2 frozen, 2 slushy and 2 liquid).

The problem can be infeasible because of at least the two following reasons.

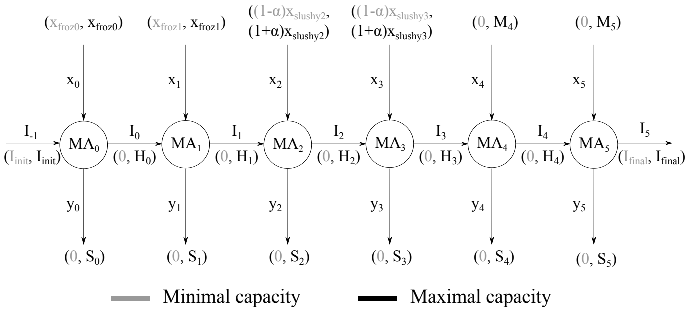

FIG. 6: An example of a minimum cost flow with capacities for MA.

- In the decentralized case, LA may change its decisions from one planning to another, thus changing the maximum supply quantities for MA. Hence, if maximum supply quantities are strongly reduced from one planning to the next, a solution in the planning i can no longer be feasible in the planning $i + 1$.
- In the stochastic case, demand forecast can change from one planning to the next, and so the same type of problem could arise. Indeed, if demand forecasts decrease, there would be less products to transport, but securing production resources constrain to produce a minimal quantity, so more products have to be stored. A storage overload may then occur.

If there is no feasible flow, we consider constraint violation is allowed to solve the problem. Only constraints added to securing production resources can be violated. This choice is motivated by the fact that if the manufacturer fails to satisfy all its constraints, constraints such as securing production resources are neither physical nor legal, but side constraints so the manufacturer can be authorized to violate these constraints. CPLEX is used to determine if the flow is feasible. If not, CPLEX can give the production constraints (x_{min}) that makes the flow infeasible, and specifies how many units need to be changed in this constraint. Thus a feasible flow exists and an optimal flow can be found.

Figure 7 shows an example where planning is not feasible. First, MA and LA's planning made at period t are presented. They are feasible planning over 4 periods. Production, transport and inventory quantities forecasted by MA and LA at the end of the negotiation process are shown in the figure. Then LA's planning is done at period $t + 1$. The logistician begins to plan based on customers demands (deterministic). Compared to his previous planning (made at period t), it should be noticed that LA transports less in period $t + 1$ to store less, and in period $t + 4$, it transports a large amount in order to reach its final stock level. The negotiation process goes on and now the producer plans with the requested quantities of LA. In MA's planning at period $t + 1$ the minimum and maximum values are presented for each decision variable. Some of these values are due to securing production resources, and others are due to capacity constraints. Thus, one can find that in period $t + 1$, it is impossible for MA to satisfy the constraints. Indeed, for his planning at period $t + 1$ MA must produce at least 3056 units at period $t + 1$ and 1588 units are already on hand from period t, so 4644 units have to be managed. But in period $t + 1$ MA can transport a maximum of 2552 units and store 2086 units, so only 4638 units can be managed. Thus, there are 6 additional units to manage in period $t+1$. In this case, the minimum amount of production would be reduced to 3050 units.

5 Experimental results

This section presents the impact of securing production resources on the economic criteria. Results are presented with the instances structure described in section 3.2.1. Cases with deterministic demand and with stochastic demand are presented. The centralized supply

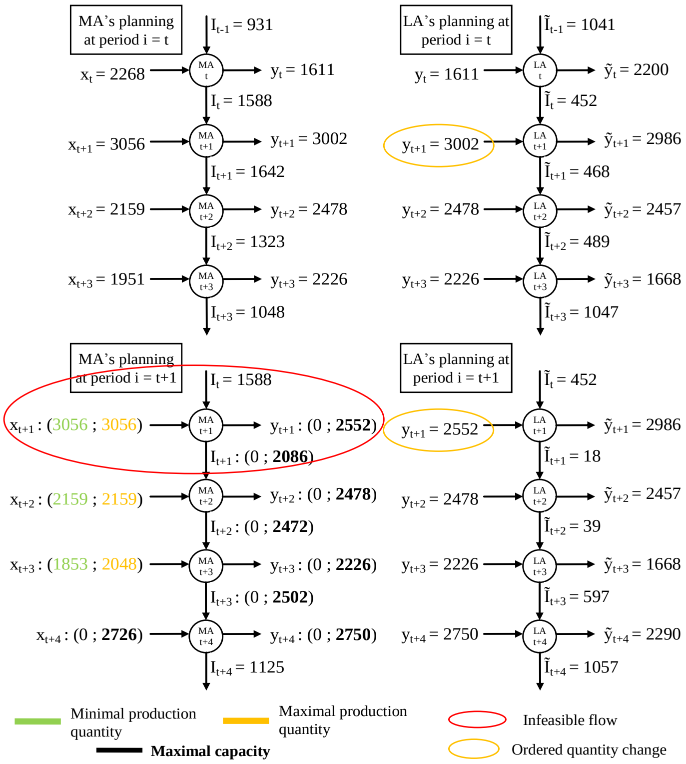

FIG. 7: An example of infeasible planning.

chain (CSCP) and the decentralized supply chain (ADSCP) are studied. The three capacities cases are also studied. The variable case is presented in this section while the fixed cases are presented in Appendices B, C and D.

5.1 Securing production resource parameters

Following the example of what is happening in industry and what can be found in the literature (Arnold and Chapman, 2004), the length of the frozen rolling horizon is set at twice the production lead time. Indeed, the frozen rolling horizon must be greater than production time in order to make no changes during the manufacturing process, and to have some margin, this duration is doubled. The production delay in the model is one period, so the length of the frozen rolling horizon is set to two periods. In addition, for periods in the slushy rolling horizon, demands should not be too inaccurate. In the model, demands are uniformly chosen between -40% and +40% of the average demand. In the stochastic case, maximal uncertainty on demand is 20% at the seventh period of planning. It can therefore be considered that slushy rolling horizon ends at this period. Thus, the first 2 periods being frozen, the length of the slushy rolling horizon is 5 periods. If the rolling planning horizon is less than 7 periods, the first 2 periods are frozen and the rest is slushy, there is no liquid rolling horizon.

The value of the flexibility coefficient α determines whether changes in the flexible periods can be strong or not. In this study, we suppose the flexibility coefficient α is given and fixed to 5%. Then a forecast production quantity for period $t+6$, between the first planning in the slushy rolling horizon (planning at period t) and the first planning in the frozen rolling horizon (planning at period $t+5$) can increase up to $((1.05)^5 - 1) \approx 27\%$ and decrease up to $(1 - (0.95)^5) \approx 23\%$.

5.2 Economic consequences while securing production resources

Here are the average results obtained on 50 instances with the parameters presented above. On the one hand cases where the supply chain is centralized (CSCP) or decentralized (ADSCP) are distinguished, on the other hand cases where demand is perfectly known (deterministic) or known with an uncertainty increasing with time (stochastic) are also distinguished. The whole planning horizon is 50 periods and results are based on the length of the rolling planning horizon considered (from 2 periods to 20 periods).

The impact of securing production resources is measured here by production, storage, transportation ans lost sales costs. Costs due to the nervousness of production (overtime, temporary staff, cancelled orders ...) are not measured here. Figure 8 presents the total cost depending on the length of the rolling planning horizon when production resources are secured, in the case of variable capacities. Results with the constant capacities case are presented in Figures C.1 and C.2. Each figure corresponds to one of the three capacities cases defined previously.

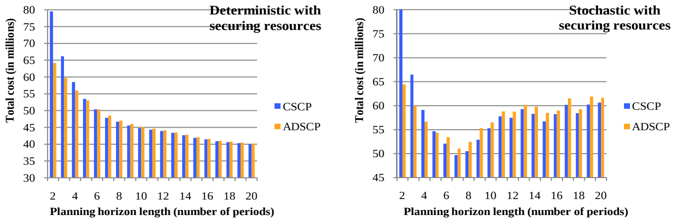

FIG. 8: Total costs in deterministic and stochastic cases with variable capacities between 80% and 120% of average demands and securing resources.

First of all, it should be noted that even with securing production resources the two previous strong results on planning are still available. In the case where capacities are fixed at 120% of average demands (Figure C.1 compared to Figure A.1), securing resources seems to have a strong negative economic impact. In other cases, it is less noticeable. Moreover, in the stochastic case costs increase when the rolling horizon is large. In order to get a better view of cost change when production resources are secured, Figures 9 and 10 show percentage changes in costs in case when resources are secured with respect to when they are not. Results with the constant capacities case are presented in Figures D.1, D.2, D.3 and D.4. These percentages are calculated as follows. Let $C_{with\ securing}$ be the average cost when production resources are secured and $C_{without\ securing}$ be the average cost without securing resources. Then, change in cost is given by the ratio $p = \frac{C_{with\ securing} - C_{without\ securing}}{C_{without\ securing}}$.

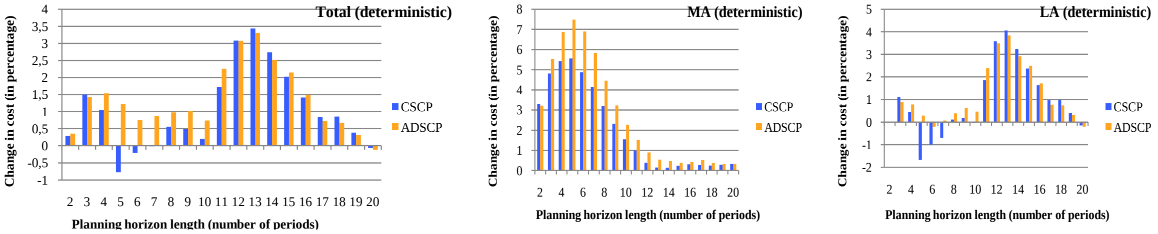

FIG. 9: Percentage of change in costs in the deterministic case with variable capacities between 80% and 120% of average demands.

From the previous graphs, the following aspects should be pointed out.

- In all cases, securing production resources incurs an additional cost for the producer. The amount of this additional cost depends on the rolling horizon length. It is generally more important when planning on 5 or 6 periods. Moreover, when there is overcapacity, this overcost is very important and can reach 25%. In other cases it is less than

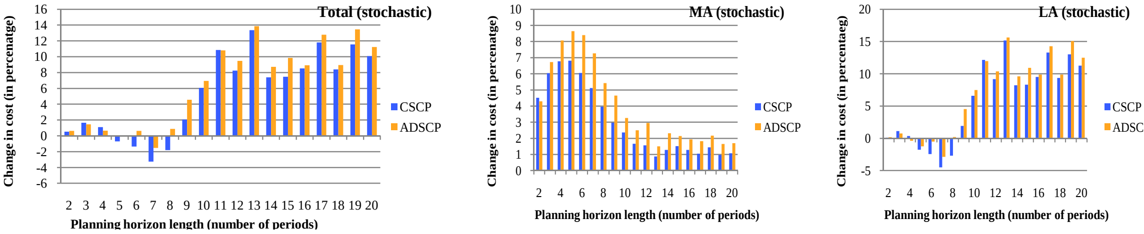

FIG. 10: Percentage of change in costs in the stochastic case with variable capacities between 80% and 120% of average demands.

10%. This additional cost is not surprising since securing production resources brings additional constraints in production planning.

- In the stochastic case, the logistician has no additional costs if the rolling horizon length is less than about 8 periods. Afterwards, the overcost becomes very important. Note that 8 periods correspond roughly to the length of frozen and slushy rolling horizons. Thus if demands are not known with certainty, securing production resources do not cost more for the logistician if it plans on the frozen and flexible rolling horizon of the manufacturer. Note that in some cases the logistician may make a slight gain.

- In the deterministic case, additional costs of the logistician are very dependent on capacities. In the case where capacities are fixed at 120% of average demands, the logistician has a fairly significant overcost in the centralized case only. In the case where capacities are fixed at 100% of average demands, securing resources has almost no impact on the logistics costs, it also permits sometimes slight gains. In the case where capacities vary, there is no significant change in the cost if planning is done on lengths less than 10 periods, then on longer lengths there is an additional cost, and when the rolling planning length reached 20 periods there is no more overcost.

- For the global supply chain, if capacities are fixed at 120% of average demands, then there is a high overcost unless demands are known on a large number of periods (at least a dozen). In other cases where capacities are more stringent, securing resources does not cost much if planning are done on the frozen and slushy rolling horizons (an overcost less than 2% in all cases). If planning lengths reach the liquid periods, the overcost can be very large (up to 14%).

Thus, as expected, it has been observed that securing production resources generally has a negative impact on the economic criterion. On the one hand, the producer's costs are increasing; on the other hand those of logistician's may also increase. The logistician which is not affected by securing production resources may find itself having to contribute to additional costs incurred. However, planning on frozen and slushy periods would incur in general only slightly higher cost.

5.3 Contributions of securing production resources

Through the previous results, let us notice that consequences of securing production resources are dependent on capacities of the supply chain. Results indicate that securing production resources is very costly in case of overcapacity. In this case, without securing resources, changes in the planed production quantities when demand forecasts are updated are easy since there is overcapacity. Hence, securing production resources is very restrictive. In the other cases were capacities are well-adapted, changes when demand forecasts are updated are more difficult since capacities are more restrictive. So introduction of securing production resource is less costly than in the overcapacity case.

Furthermore, even if securing production resources has a cost, costs related to sudden changes in production forecasts (working force and supplier) had not been taken into account when there is no securing production resources. From our experimental results, only the case where demands are not known with certainty and where rolling horizon is long has a very important overcost (about 10% for variable capacities and fixed capacities at 100% of the average demands and about 30% for fixed capacities at 120% of the average demands). However, this case is the least relevant to an industrial point of view since it had already been shown that when demands are not known with accuracy it is useless to anticipate too much.

With the goal of having a more sustainable supply chain, let us compare the solutions obtained with and without securing production resources. Results are shown in Figure 11 for a rolling planning horizon on frozen and slushy periods (between 2 and 8 periods), and in Figure 12 for a rolling planning horizon on liquid periods (between 9 and 20 periods). These results only concern the decentralized supply chain. For the economic criterion, the cost increase as a percentage relative to the optimal solution (one of the 50 planning periods) is used. For the social criterion, the number of changes in production quantities just before the completion of the production is considered. Results presented are averages over the results of different rolling horizons. In each figure, the three capacities cases are presented with deterministic and stochastic demands.

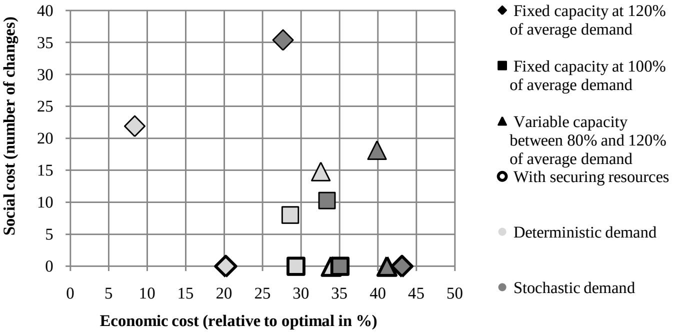

FIG. 11: Economic and social performance of solutions with a short rolling planning horizon.

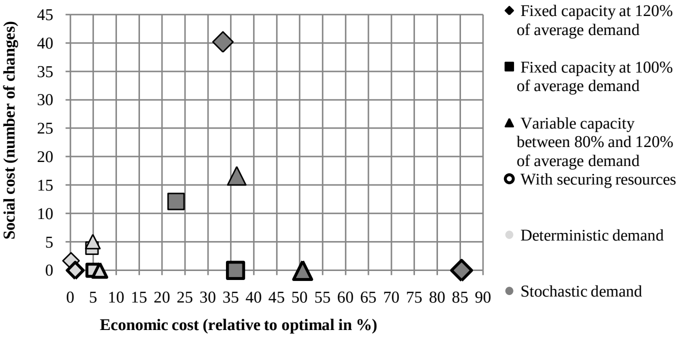

FIG. 12: Economic and social performance of solutions with a long rolling planning horizon.

Furthermore, Table 5 presents the pros ans cons of a planning with securing production resources compared to a planning without securing resources. A '=' means that the criterion is not significantly altered, a '+ ' or '+ +' means the criterion is improved respectively a little or a lot, and a '- ' or '- -' means the criterion is degraded, respectively a little or a lot. The cases where demands are accurately known or not, and where the rolling horizon is short or long are distinguished. Based on the Figure 11 and Figure 12, it is clear that (a) costs increase if demand is accurately known and planning is done on a small rolling horizon, and (b) costs increase significantly when trying to anticipate a demand which is not accurately known. However (c,d) with a short-term rolling planning, very poorly managed resources are now secured, and (e) with a long-term rolling planning with imprecise demand forecasts, securing resources helps to avoid mismanagement of resources. The case (d) is very interesting because a better securing production resources is clearly possible with a low overcost. And planning on a small rolling horizon with demand uncertainty is very usual in the industrial world.

		Costs	Resource stability
Deterministic demand	Short rolling horizon	- (a)	++ (c)
	Long rolling horizon	=	=
Stochastic demand	Short rolling horizon	=	++ (d)
	Long rolling horizon	- - (b)	+ (e)

TAB. 5: Positive and negative aspects of securing production resources.

6 Conclusion and prospects

This paper has proposed to revisit Jung et al.'s model permitting to model decentralized supply chain planning. Starting from this model, we have brought industrial reality aspects: rolling planning horizon with short term vision and securing production resources.

Supply chain actors often have a short demand vision, and this vision may even be distorted depending on the temporal distance. Hence, we have proposed to make a planning on a rolling horizon basis: each period the actors plans on a small rolling horizon length. It is then possible to make a long term planning simulation. Moreover, we have studied a stochastic case where demand is known with an uncertainty increasing with the temporal distance. The two major results are: (1) decentralized planning can be better than centralized planning when planning with a small rolling horizon length, and (2) if demand forecast is not reliable, it is useless to anticipate too much.

However, it has been raised that under rolling planning horizon, decisions can be fully questioned. In the case of production decisions this implies poor social management. So it would be better to fix the planning on the closest periods. Thus, the economic criterion have no longer been considered solely, social constraints have been integrated based on the rolling planning horizon division, that permit to secure production resources.

Then, consideration has been given to costs changing when the social constraint is integrated. Three different cases of capacities in the supply chain have been considered. Results clearly indicate that securing production resources is costly when there is global overcapacity. When capacity is globally well adapted, securing production resources is not very expensive when planning on a small rolling horizon (less than 8 periods). The additional cost is approximately 2%, and resource stability is improved. However, if demands are not known with accuracy, too much anticipation when planning is costly, and securing production resources generates a significant additional cost between 10 and 15%. Thus, when planning on rolling horizon basis between two actors in a decentralized supply chain, if demand is known shortly in advance then the establishment of a securing production resources provide a social benefit with few overcosts.

Future prospects are directed along four axes. On the one hand, to extend this work it could be interesting to study the impact of securing resources parameters on supply chain costs. Thus we could determine whether a relation exists between the lengths of frozen and slushy rolling horizon, and the length of the rolling planning horizon from which overcost increases in the stochastic case. The impact of the flexibility percentage on the overcost should also be studied.

In addition, changes introduce by the securing production resources permit the construction of a planning, considering data update, but without too much change in the previous planning. This seems close to the robust planning approaches, so it would be interesting to compare the two approaches.

Another prospect is to enrich the supply chain model. That is to say, to gradually extend to a multi-actor, multi-level and multi-product supply chain.

Moreover, it would be interesting to study other negotiation processes that improve the performance of the decentralized supply chain, while seeking to exchange the minimum information between the different actors. For example, the producer should be authorized to increase quantities proposed by the logistician, thus some lost sales could be avoided.

Acknowledgments

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Appendices

A Evolution of total costs without securing resources

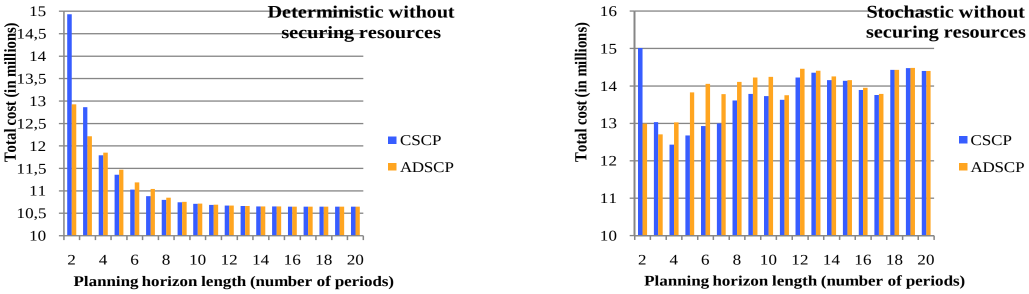

FIG. A.1: Evolution of the total cost in deterministic and stochastic cases with fixed capacities at 120% of average demands.

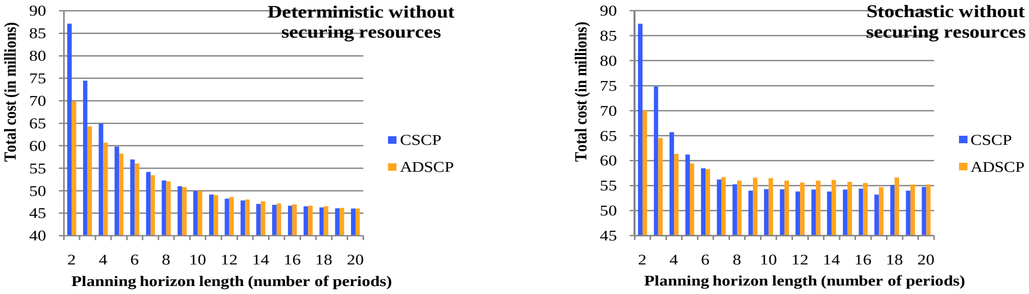

FIG. A.2: Evolution of the total cost in deterministic and stochastic cases with fixed capacities at 100% of average demands.

B Differences between forecast and completion

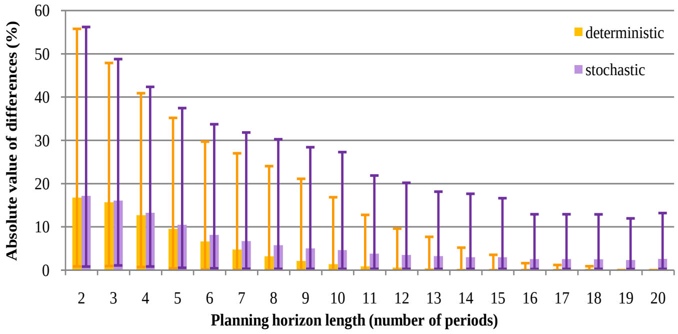

FIG. B.1: The percentage differences between the forecast at a time t and the completion of production at period $t+1$ with fixed capacities at 120% of average demands.

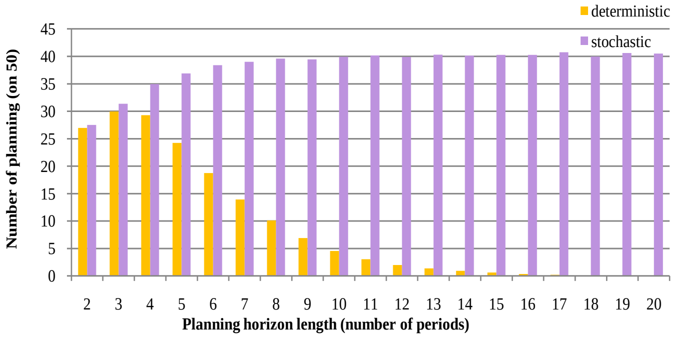

FIG. B.2: Average number of planning for which there is a gap between forecast and completion with fixed capacities at 120% of average demands.

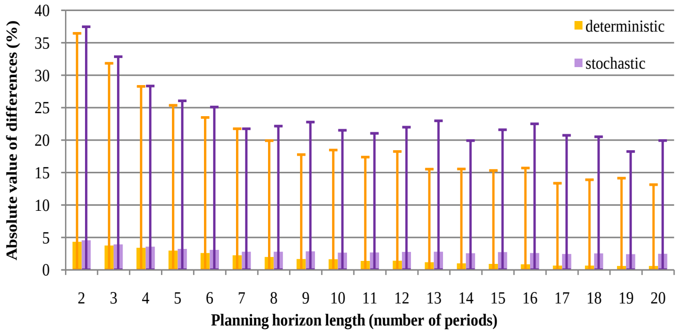

FIG. B.3: The percentage differences between the forecast at a time t and the completion of production at period $t+1$ with fixed capacities at 100% of average demands.

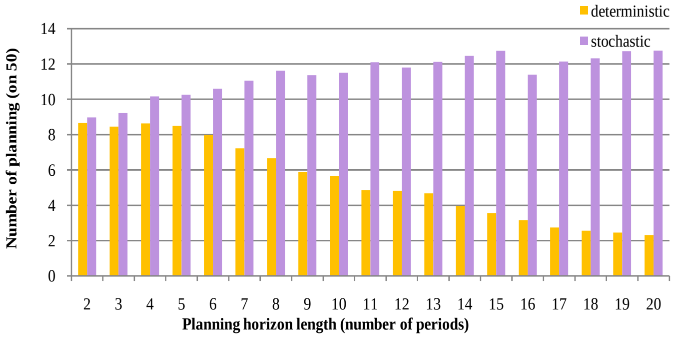

FIG. B.4: Average number of planning for which there is a gap between forecast and completion with fixed capacities at 100% of average demands.

C Total costs with securing resources

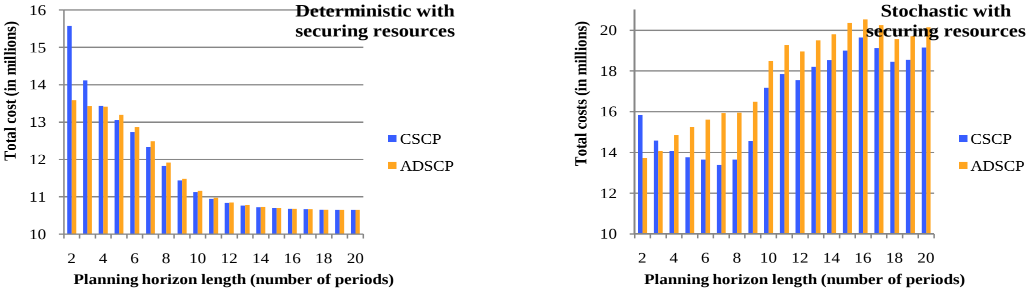

FIG. C.1: Total cost in deterministic and stochastic cases with fixed capacities at 120% of average demands and securing resources.

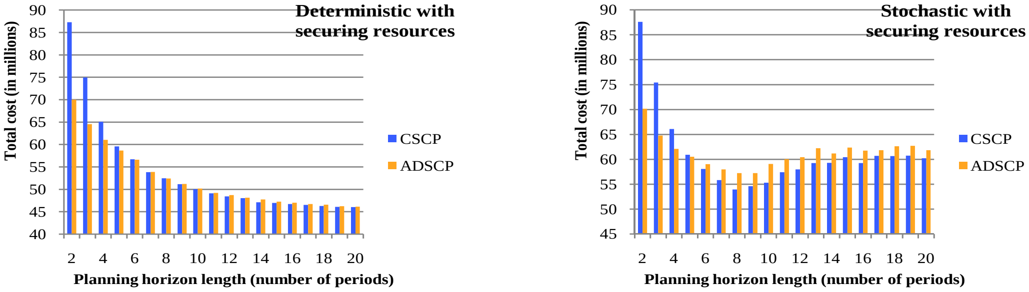

FIG. C.2: Total cost in deterministic and stochastic cases with fixed capacities at 100% of average demands and securing resources.

D Change in costs

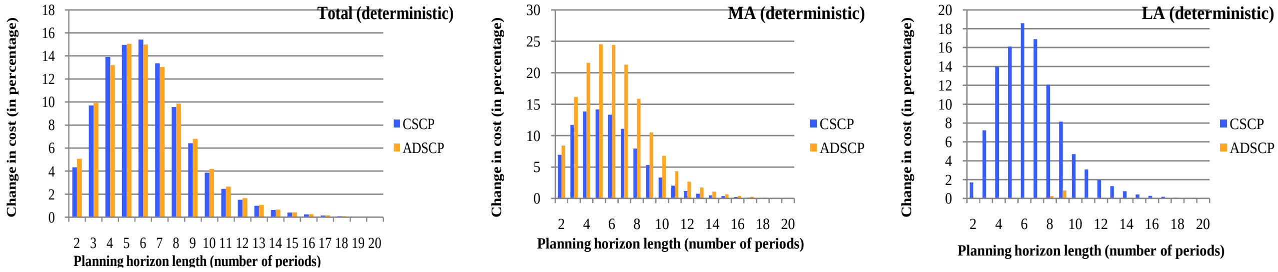

FIG. D.1: Percentage of change in costs in the deterministic case with fixed capacities at 120% of average demands.

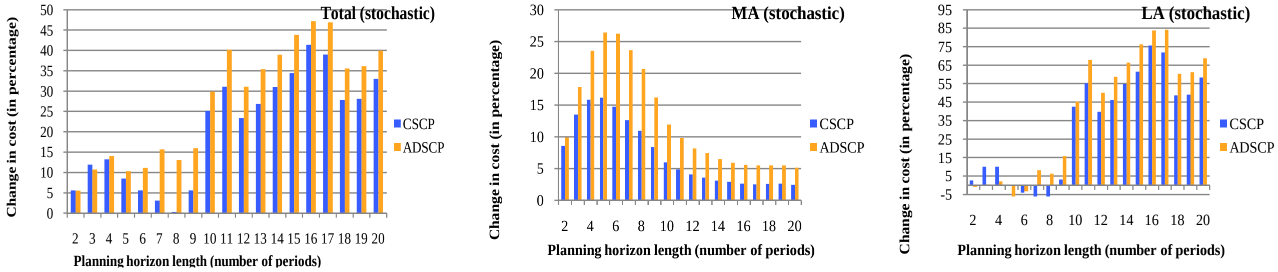

FIG. D.2: Percentage of change in costs in the stochastic case with fixed capacities at 120% of average demands.

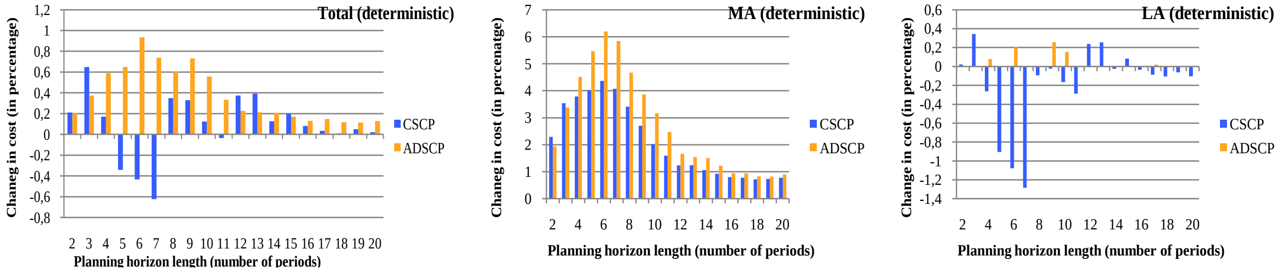

FIG. D.3: Percentage of change in costs in the deterministic case with fixed capacities at 100% of average demands.

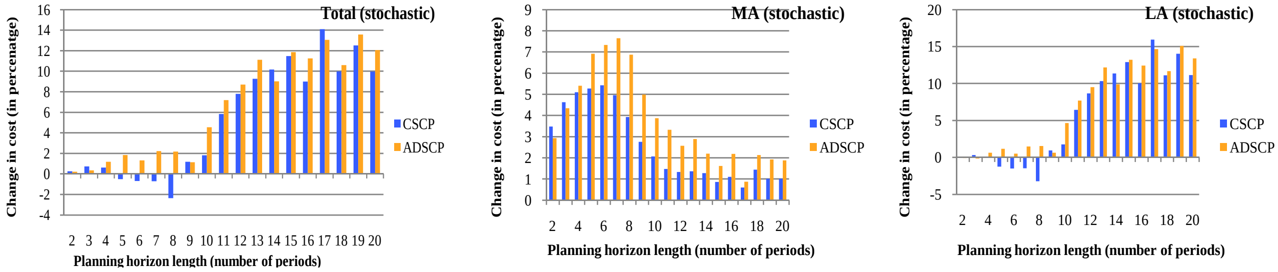

FIG. D.4: Percentage of change in costs in the stochastic case with fixed capacities at 100% of average demands.

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