

Multi-Agent Coordination Based on Tokens: Reduction of the Bullwhip Effect in a Forest Supply Chain*

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ABSTRACT

In this paper, we focus on the supply chain as a multi-agent system and we propose a new coordination technique to reduce the fluctuations of orders placed by each company to its suppliers in such a supply chain. This problem of amplification of the demand variability is called the *bullwhip effect*. To reduce such a bullwhip effect, we propose a technique based on tokens to achieve a decentralized coordination. Precisely, classical orders manage the demand itself whereas tokens manage effects on company inventory due to variations of this demand. Finally, the proposed approach is validated by the Wood Supply Game, which is a supply chain model used to make players aware of the bullwhip effect. We experimentally verify that our coordination technique leads to less variable orders (i.e. the standard deviation of orders is reduced) while inventory levels are not excessively high but sufficient to avoid backorders.

Categories and Subject Descriptors

I.2.11 [Distributed Artificial Intelligence]: multi-agent systems

General Terms

Management, performance, experimentation

Keywords

Multi-agent systems, supply chain, decentralized coordination, tokens, bullwhip effect

1. INTRODUCTION

The performance of many systems is reduced by fluctuations in their internal streams. As a distributed system, a multi-agent sys-

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tem may face this problem too. In this paper, we focus particularly on supply chains, which are systems composed of different companies producing and distributing products to customers. In a supply chain, fluctuations affect order streams (cf. Figure 1): the point of sale places quite constant orders to its suppliers, whereas these suppliers place more variable and unpredictable orders. This problem, which is known as the *bullwhip effect*, leads to unnecessary inventory and decreased customer service due to backorders, that is inventory shortages. Our goal is to improve supply chain efficiency by reducing demand amplification while keeping a low inventory and good customer service. We present all these problems in Section 2. The bullwhip effect is a coordination problem between autonomous companies [6] which can be considered as agents, therefore we have looked for a coordination technique in multi-agent system and production management fields (e.g. [1], [7], [8], [18], [21] and [25]). The required techniques need to preserve the autonomy of system entities (no central coordination) and to avoid entities transmitting their own information to other entities (communication load reduction). To this end, we think the most appropriate technique to reduce the bullwhip effect is based on tokens. Coordination based on tokens is unknown as such in the multi-agent field to the knowledge of the authors ([20], [2]), but it can be seen as a lower level to coordination based on communication. Such techniques exist in production management where tokens are exchanged between production units to manage production in a decentralized way. Basically, the idea supporting our coordination mechanism is to divide orders in two parts: the first one is the classical order and is used to manage the real time demand itself, whereas the second part is a token used to *manage fluctuations* in the first information part. More precisely, classical orders travel up the supply chain to make companies know what the market buys and tokens travel up the supply chain to broadcast how many products more or less compared to market consumption each company needs to keep steady inventory. By doing so, we use tokens to coordinate participants in the supply chain around the market demand, thus reducing the bullwhip effect. As this coordination technique is decentralized and computable, it can be considered as a new multi-agent coordination technique. We present this technique in Section 3. Finally, we validate this technique on a supply chain model derived from the Wood Supply Game [9, 11] taking the Québec (a Canadian province) forest industry into account. This game is an adaptation of the Beer Game [27] for the forest industry; this latter game was designed to make players aware of the bullwhip effect. Section 4 gives a detailed presentation of the validation of our mechanism.

2. THE PROBLEM

In this section, we first describe the fluctuation problem from a general point of view, then we focus on a concrete example of this problem in the supply chain field. The stream fluctuations in supply chains (a supply chain is the set of companies producing and distributing products to consumers) affect orders placed by companies to their supplier(s); this is known as the bullwhip effect.

2.1 Fluctuations in distributed systems

The fluctuation problem in a distributed system can be described as follows: (i) a distributed system (multi-agent or other) is built to achieve a function; (ii) many streams travel in the distributed system while achieving its function; (iii) these streams may fluctuate; (iv) these fluctuations may trouble the distributed system in achieving its function.

Stream fluctuations may arise in many distributed systems: (i) on the road network, vehicle density may fluctuate, generating traffic jams and empty roads instead of steady traffic on every road, (ii) on a computer network, data density between computers may fluctuate, generating congestion, (iii) in electronics, electricity may fluctuate between components, roasting electronic components, (iv) in the macro-economy, the economy of a country alternates among recession and growth, etc. We focus in the two following subsections on two examples: multi-agent systems and supply chains.

2.2 Fluctuations in multi-agent systems

As multi-agent systems are particular distributed systems, fluctuations may occur in them. Parunak [22] notes that, in principle, systems of autonomous agents can become computationally unstable. We think this instability may appear in this way: to carry out its function, a multi-agent system is crossed by two streams: an actions stream resulting from other agents and a percepts stream resulting from the environment and from the others agents: if a stream is disturbed (delay, error...), the other is disturbed as well. In particular, an instability may occur due to the following causes: uncertainty in evaluating the environment, delay in information transmission, multithreading management if several agents run on the same processor, etc. In some cases, in particular if the multi-agent system represents a supply chain, the global behavior of the multi-agent system can be perturbed by these fluctuations.

2.3 Fluctuations in supply chains: the bullwhip effect

We now illustrate this problem using the case of unexpected demand fluctuations in a supply chain which is known as “amplification of the demand variability”, “bullwhip effect” or “Forrester’s effect”. The entities of such a supply chain are companies and the fluctuating streams in this system are the orders placed by each company to its suppliers. Figure 1 shows how the bullwhip effect propagates on a simple supply chain with only three companies: a retailer, a wholesaler and a manufacturer. The retailer sells to the customer and buys from the wholesaler, the wholesaler sells to the retailer and buys from the factory and the factory sells to the retailer and buys from an unknown supplier. The ordering patterns of the three companies share a common, recurring theme: the variabilities of an upstream site are always greater than those of the downstream site [14]. As a variability, the bullwhip effect is measured by the standard deviation σ of orders (note that means μ of orders are all equal in our example). Demand fluctuations cost money due to higher inventory levels and supply chain agility reduction (agility is the ability of an organisation to thrive in a constantly changing, unpredictable business environment [12] in [24]). In fact, such fluctuation of the demand lead every participant in the supply chain

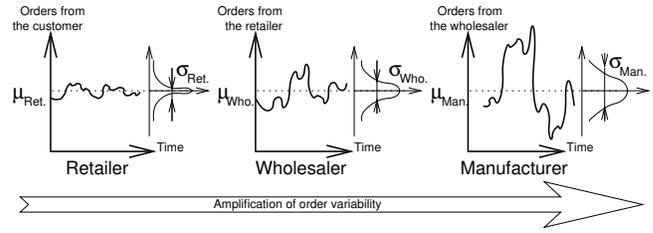


Figure 1: The bullwhip effect [15, 16].

to stockpile because of a high degree of demand uncertainties and variabilities [15].

The demand fluctuation in a supply chain was first described by Forrester [10] in 1958 and this explains why this phenomenon is sometimes called the Forrester’s effect. Many years later, Lee and his colleagues [14, 15] gave a more complete understanding of this effect and called it the *bullwhip effect*. They proposed in particular four main causes (demand forecast updating, order batching, price fluctuation, and rationing and shortage gaming). However, some other causes were identified [10, 27, 28]. A formal model of this problem was proposed in [4] but very few people [13, 29] studied this problem using multi-agent techniques. Simchi-Levi and his colleagues [4, 26] note that one of the most frequent suggestions for reducing the bullwhip effect is to centralize demand information within a supply chain, that is, to provide each participant in the supply chain with complete information on the actual customer demand (this was formally proven for two forecasting techniques in). Such centralization of information allows every company in the supply chain to create more accurate forecasts, rather than relying on the downstream company, which can vary significantly more than the actual customer demand. In our validation, we try to compare our coordination mechanism with this centralization.

Finally, reducing the bullwhip effect appears to be more a problem of coordination rather than of optimization, of constraints satisfaction or of any other type of problem, because, for each company, it is a matter of ordering in a coherent manner in comparison to other company’s behaviour. The goal is to synchronize every company’s activities in order to avoid products being stored in inventory.

3. DECENTRALIZED COORDINATION BASED ON TOKENS

Our coordination technique aims at improving system efficiency by reducing stream fluctuations between entities. We first look at two decentralized coordination mechanisms based on tokens used in the production management field. We then present the technique we propose generally for any multi-agent system. Finally, we apply this general idea to reduce the bullwhip effect, that is the amplification of demand variability in a supply chain.

3.1 Tokens as a coordination mechanism

In the field of Industrial Management, several different approaches have been proposed and are used in some companies to coordinate production entities in manufacturing systems in a decentralized way. These approaches use *tokens* to coordinate entities. Many mechanisms were proposed: at the company level, PAC (Production Authorization Cards) System [3], Kanban, Extended Kanban and Generalized Kanban [17] are used to control the production of one company and at the supply chain level. Responsibility Tokens [23] is the operationalization of the Lee and Whang’s [16]

3.3 Example of token-based coordination in a supply chain

Each company in the supply chain can be controlled by a software agent; therefore the supply chain can be viewed as a multi-agent system. *Improving coordination in the multi-agent system will reduce the bullwhip effect* while improving supply chain efficiency. We apply to the supply chain the general idea of our coordination technique as stated previously. Here, for agent i , upstream agent $i - 1$ is company i 's customer and the environment is the market. Information streams are composed of orders placed by each company to its suppliers. We now cut these streams into two parts (Figure 4): the first part X represents the actual quantity desired by the company to satisfy its orders (we call this part the order because it is the classic flow) and the second part Y_i allows company i to over- or underorder when there is a change in the incoming order X (we call this part tokens). The information given to company i by company $i - 1$ is the doublet (X, Y_{i-1}) . If incoming order X increases, each company's inventory reduces as long as ordered products arrive: so tokens Y_i manage the consequences of delays in physical and information streams. The idea is that orders X exactly follows market demand, that leads to the same fluctuations in orders as in the market; *the bullwhip effect is thus eliminated* (as do 1-1 ordering rule) because order fluctuations are the same as markets ones. But this can lead to huge inventories or backorders (i.e. negative inventories), so we introduce tokens Y_i to manage a *unique over- or underorder* for each change in the market to stabilize each company's inventory. X indicates thus the market need and is the same for every company in the supply chain. Y_i indicates a variation in X and allows each company to maintain an efficient inventory (i.e. not too big, not too small). When customer demand increases (or decreases) because of a market demand increase (or decrease), the job of tokens is to travel up to the forest to trigger off only one big (or small) quantity to go down the supply chain to adjust each company's inventory to its normal level. This is the theory: to react more quickly to the increase in customer demand, we do not wait for tokens to go to the forest before triggering bigger shippings: each time a company receives a token, it processes it as an order; if it does not have enough inventory, the remaining tokens are memorized as backordered tokens.

Coordination with tokens and information centralization (i.e. each company knows in real time the actual market demand) both allow every company to know the actual market demand. In fact, when tokens are used, order X is equal to market demand. The first difference between these two systems lays in market demand propagation speed: tokens are as slow as orders while information centralization supposes each company knows in real time the market demand (retailers broadcast the market consumption to the whole supply chain). The second difference between tokens and information centralization is with customer demand management. With information centralization, when the retailer overorders to reconstitute its inventory, its wholesaler has to overorder even more in order to reconstitute its own inventory, and so on. In this situation, all companies place orders superior to what is asked by their customer because it is their only way to refill their inventory. They do so even if they know what the customer demand is and that this causes their suppliers to be in backorder. On the contrary, when the retailer sends tokens to its wholesaler, it indicates that it needs more products to reconstitute its inventory: it continues to place the same orders as its incoming orders are, to avoid perturbations in the rest of the chain (in particular, it does not put its suppliers into a backorder situation) and waits for incoming products streams to bring the *products wave* ordered with tokens in order to adjust its inventory level.

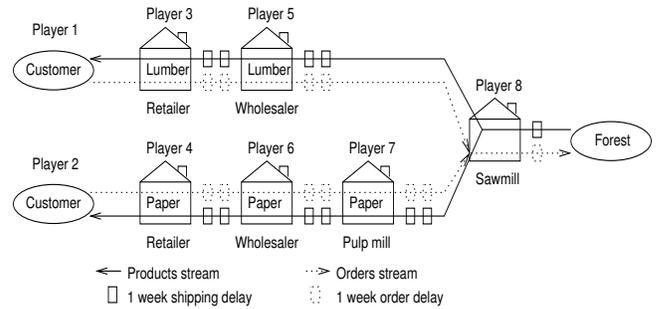


Figure 5: Model of forest supply chain used in experiments.

4. EXPERIMENTAL VALIDATION

We have validated our coordination mechanism on a model of a forest supply game which simulates the group of companies participating in the production and distribution of paper and lumber. This model is first described and then the experiments are detailed.

4.1 The wood supply game

Two games, called “Wood Supply Games” [9, 11], were developed based on the structure and dynamics of the Beer Game. Beer and Wood Supply Games are an exercise that simulates the material and information flows in a production-distribution system and were designed to make players aware of the bullwhip effect. Compared to the classical Beer Game that has been used to study supply chain dynamics, the Wood Supply Games introduce divergent product flows to increase its relevance to the North European forest sector. Our team has adapted this game for the Québec forest sector; we use this version, which is displayed in Figure 5. There are eight players in this figure, but both customer players are only there for convenience when drawing figures 12, 13 and 14. The main difference between the original and our Québec Wood Supply Game is in the length of the lumber and paper chain which is either the same (Fjeld's game) or different (our game).

Figure 5 shows how six players (human or software agents) play the game. The game is played by turns: each turn represents a week in reality and is played in 4 steps; these 4 steps are played in parallel by each player. In the first step, players receive their inventory (these products were sent two weeks earlier by their supplier, because there is a two-week shipping delay) and advance shipping delays between suppliers and their customers. Then in the second step, players look at their incoming orders and try to fill them. If they have backorders, they try to fill those as well. If they do not have enough inventory, they ship as much as they can and add the rest to their backorders. In the third step, players record their inventory or backorders. In the fourth step, players advance the order slips. In the last step, players place an order to their supplier(s) and record this order. To decide what the order to place is, players compare their incoming orders with their inventory/backorder level (in our experiments, they only evaluate what is written in Figure 7). The *correct decision* that would reduce the bullwhip effect has to be taken here. Finally, a new week begins with a new step 1, and so on. Each position is played in the same way, except the sawmill: this position receives two orders (one from the lumber wholesaler, another from the pulp mill) that have to be aggregated when placing an order to the forest. The sawmill can evaluate its order by basing it on the lumber demand or on the paper demand: in the following experiments, the sawmill places an order equal to the maximum of this two possible orders. Moreover, the sawmill receives one type of product and each unit of this product generates two units: a lum-

	Without information centralization	With information centralization
Without tokens	Experiment A	Experiment C
With tokens	Experiment B	Experiment D

Figure 6: Experiments classification.

Exp	Order placed X	Tokens sent Y_i
A	incoming order minus inventory variation	none
B	incoming order	incoming tokens plus 2 times order variation
C	customer demand minus inventory variation	none
D	customer demand	incoming tokens plus 2 times customer demand variation

Figure 7: Experimented ordering patterns.

ber and a paper unit. That is, each incoming unit is cut in two: one piece goes to the sawmill's lumber inventory, the other goes to its paper inventory.

When we add our coordination technique to this game, players have to manage tokens. If players receive tokens with incoming orders in the second step, they should transmit them minus the products shipped in the second step. As the incoming orders change (they always change at the same time as tokens arrive), players add the new tokens to the transmitted tokens; in our experiments, we have empirically chosen the quantity of added tokens to be equal to two times the incoming order variation (cf. experiments B and D in Figure 7). Generally, this quantity of added tokens depends on incoming order variation, on transportation delays and on ordering delays.

4.2 Experiments

We measure order variability by computing the standard deviation σ of orders placed by each company in the supply chain. This measure is made in the four experiments described in Figures 6 and 7: each either uses or not information centralization (each player knows in real time the customer demand) and our coordination mechanism. We now present the results of each experiment and conclude with some comparisons.

4.2.1 Experiment A

Experiment A uses neither information centralization nor any coordination mechanism. It is the most basic experiment with which the other three experiments are to be compared. Players order from their upstream player what their downstream player ordered minus their stock variation. This order pattern is designed to keep positive inventory: when incoming orders are greater than stock variation, the quantity ordered will keep a steady inventory, but when incoming orders are not greater than stock variation, nothing is ordered (there are no negative orders, i.e. order cancellations), leading to an increase in inventory.

Figure 8 exhibits the quantity ordered each week by each player. The first curve gathers lumber and paper customer demands, the second one represents orders placed by lumber and paper retailers, the third one shows both wholesalers orders, the fourth one shows

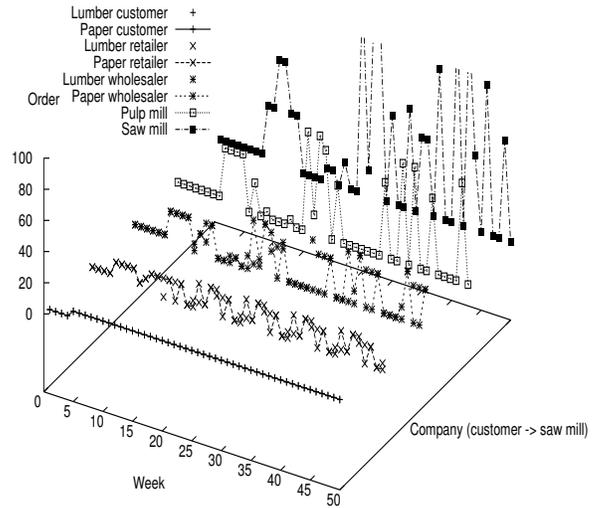


Figure 8: Experiment A (without information centralization, without tokens).

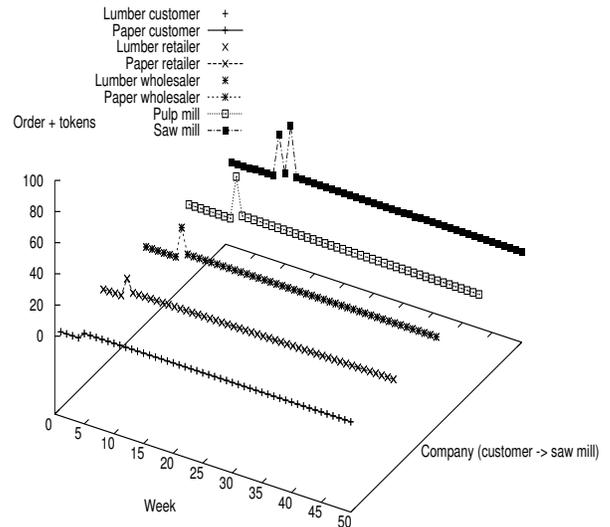


Figure 9: Experiment B (without information centralization, with tokens).

only pulp mill orders and the last curve is for the saw mill. We can see a very great amplification in order variability between the two first curves (lumber and paper customer) and the last curve (saw mill), that is the bullwhip effect is huge. The third curve gathers lumber and paper wholesalers' orders: they do not order the same quantity all the time. This is because the supply chain is a system where the lumber chain is shorter than the paper one, therefore players order in a different manner even if they have the same ordering pattern.

4.2.2 Experiment B

Experiment B uses our coordination mechanism but not information centralization: only the retailer knows the customer demand. That is, we only added our coordination mechanism to experiment A. The order placed by players is equal to their incoming order (we don't subtract inventory variation as in experiment A, because this variation was there to keep steady or positive inventory and this is now the job of tokens). Some tokens are added to this order which quantity is the sum of incoming tokens plus two times the incoming order variation: the incoming tokens represent the transferred tokens while the two times the incoming order variation is an evaluation of the needed quantity to refill inventory. Figure 9 exhibits the ordering pattern for each player. In this Figure, tokens are added to orders, which leads to a peak in ordering pattern when a company becomes aware of changes in market demand. Moreover, we can see that this peak does not happen at the same time: there is a two-week shift between two successive supply chain levels (e.g. between retailers and wholesalers) due to order delays. As the saw mill belongs to lumber and paper supply chains and these two chains have different lengths, the saw mill has two peaks. Figure 9 can be compared with Figure 8; we can see that fluctuations in orders are not as great in experiment B as in experiment A, so *tokens lower the bullwhip effect*.

4.2.3 Experiment C

In comparison with experiment A, experiment C adds information centralization (but not tokens as in experiment B). Experiments C and D use this centralization, which allows players to base their order on customer demand instead of on incoming orders. This explains the difference in the ordering formula between experiments A and B in that we replace "incoming order" with "customer demand". So, players now order customer demand minus their own inventory variation. In experiment B, players are also able to know customer demand (this demand travels upstream in the order, without being affected by anything else such as downstream player's inventory variation) but this signal is very slow (as slow as orders: two weeks are needed to go from players to their suppliers). Compared with experiment A, we now assume that customer demand is instantaneously known by all players. When comparing Figures 8 and 10, we have a confirmation that information centralization reduces the bullwhip effect ([4, 26]).

4.2.4 Experiment D

Experiment D uses information centralization and tokens (cf. figure 11). Players now order customer demand and send tokens. The quantity of these tokens is the number of incoming tokens plus two times the customer demand variation. If we compare Figures 11 and 9¹, where we have tokens in both experiments, we can see the information centralization advantage: (i) all peaks occur early and (ii) peaks are equal. We can note there are several peaks for each company: the first peak corresponds to tokens sent

¹In both experiments B and D, Figures 11 and 9 exhibit the sum of orders plus tokens.

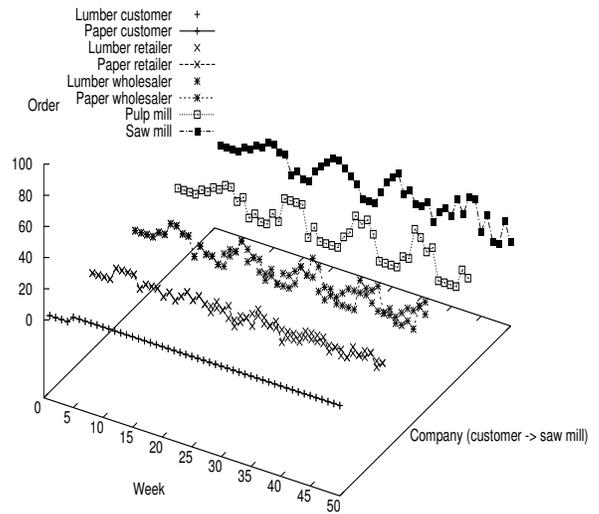


Figure 10: Experiment C (with information centralization, without tokens).

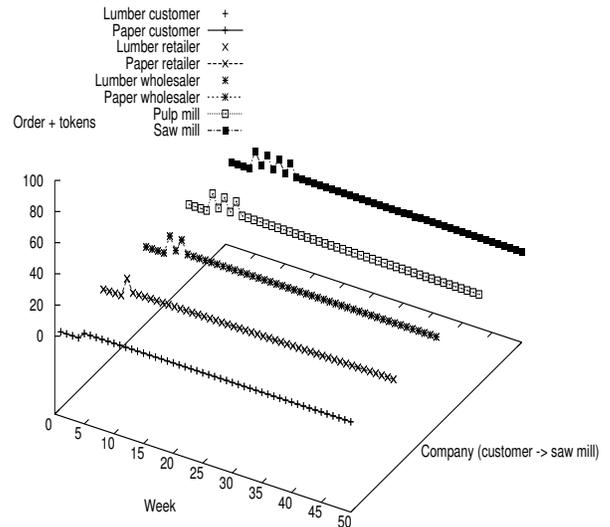


Figure 11: Experiment D (with information centralization, with tokens).

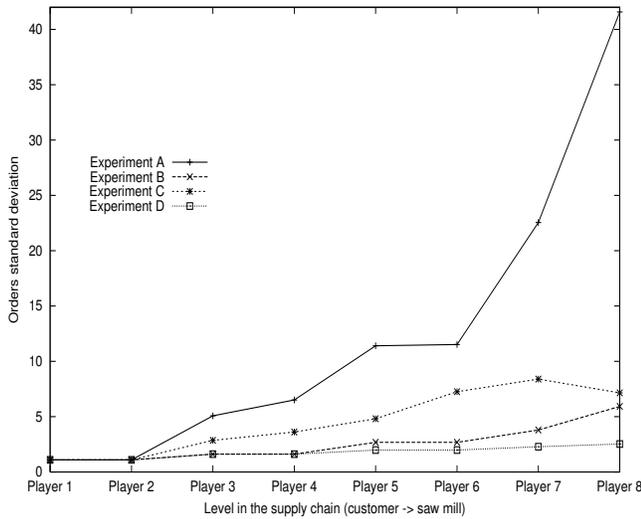


Figure 12: Standard deviation of orders.

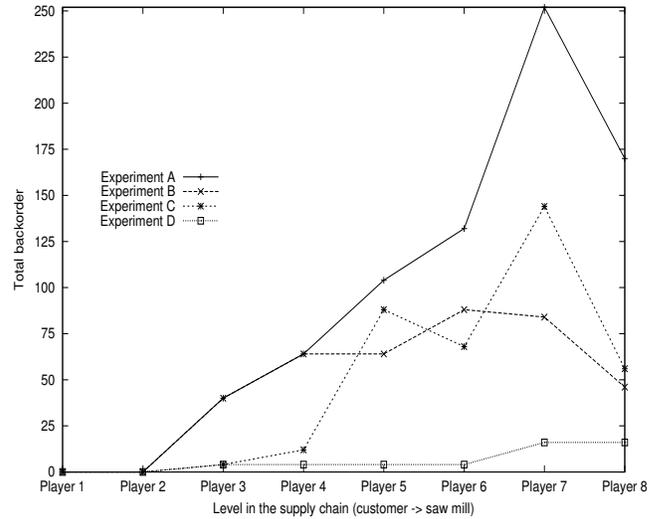


Figure 14: Total backorders for each player.

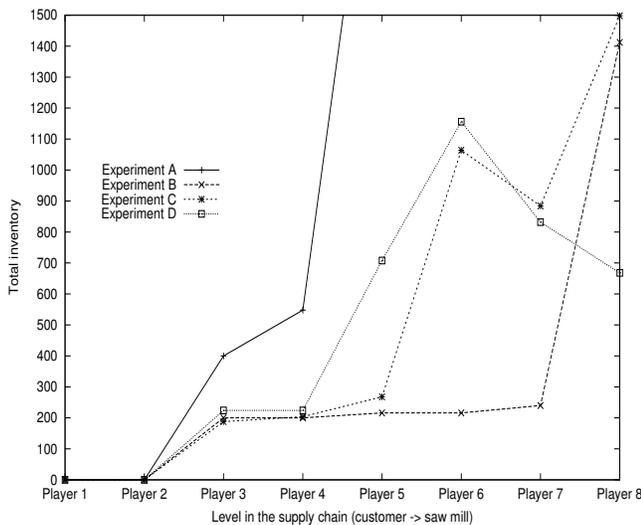


Figure 13: Total inventories for each player.

by the company and the next ones are the tokens transmitted from clients.

4.2.5 Experiment comparison

Figure 12 shows standard deviation of orders for each company (Figure 5 gives the company name for each player) and for each experiment on 50 weeks. The lower this standard deviation is, the lower the bullwhip effect: in the best case (experiment D), the standard deviation for each company is inferior to 2.53 (sawmill) while the customer's is 1.09. It does not seem possible to reduce the companies standard deviation to 1.09, because companies have to overorder to reconstitute their inventory due to delay effects. If companies do not do so, it would mean that inventories are too low or even negative, i.e. companies have backorders, which thus reduces customer service.

Only experiments that use tokens (B and D) finish with stable order patterns, while customer demand is always stable, except in week 5 where there is a unique change. In all experiments, no

company finishes the game with backorders. In experiments B and D, some companies finish with very few products in inventory: as they have a stable order pattern, this can be seen as an excellent result. On the other hand, we have chosen the factor two in the tokens created in order to reconstitute original inventories: we think this heuristic factor corresponds to the ordering delay, because the longer the ordering delay is, the more inventory decreases and so the more tokens are to be sent. But this factor depends on the shape of the supply chain too (e.g. in experiment D, the lumber wholesaler's inventory stabilizes on 16 products in inventory per week, while the paper wholesaler's inventory stabilizes on 28). This is a consequence of the divergent flow located in the saw mill and of the different sub-supply chain lengths. Next, tokens lead to more stable order patterns (i.e. less bullwhip effect) than information centralization: experiment A and C curves are above experiment B and D. But this does *not* mean that our coordination mechanism is always better than information centralization.

In fact, when we look at Figures 13 and 14, we see that total inventory and backorder curves cross: this means some companies prefer to manage the supply chain like in the experiment D while some others prefer to manage like in experiment B or C (never A) if their goal is to minimize only their inventory. However, *experiment D has the best results* because it has the lowest bullwhip effect and the lowest backorders (i.e. the best customer service) for each company. Moreover, inventories in experiment B are lower than in D for every company, but this inventory may be adjusted by changing the heuristic factor of sent tokens. In fact, when too much tokens are sent, inventories stabilize on a too important level: as we calculate total inventories on 50 weeks, a little difference on the inventory stabilization level leads to huge difference in Figure 13 (and also 14).

5. CONCLUSION

In this paper, we have investigated coordination techniques that are able to reduce streams fluctuations in a distributed system. We have proposed a new coordination technique to manage this fluctuation in a decentralized way and applied it to the case of a supply chain. In fact, a supply chain is a distributed system composed of many companies where the fluctuation problem is the amplification of demand variability called the bullwhip effect. Our tech-

nique uses tokens to achieve the coordination in a decentralized way; these tokens may also be seen as a negative feedback which stabilizes the supply chain by sharing information on demand. We have validated this technique using a supply chain model which is an adaptation of the Wood Supply Game to the Québec forest industry. These experiments have shown that token-based ordering rules are better in general than others. Moreover, information centralization improves our mechanism.

Further validation could be done to complete this study. Firstly, we have to test how our coordination technique behaves with other customer demand than a unique increase. We could test unique decrease, constant increase and decrease, different seasonalities, etc. Secondly, the quantity of tokens to send has to be studied to understand what is the optimal quantity to send depending on the supply chain shape and on the shipping and ordering delays. Finally, we have validated our coordination mechanism on a very simple example of supply chain and it would be very interesting to adapt it to our more complex model [19].

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