BULLWHIP EFFECT AND SUPPLY CHAIN MODELLING AND ANALYSIS USING CPN TOOLS

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Abstract. The paper presents some of the results obtained by studying Petri nets' capability for modeling and analysis of Supply Chain performances. It is well known that the absence of coordination in Supply Chain management causes the so-called Bullwhip Effect, in which fluctuations in orders increase as they move up the chain. A simple three-stage supply chain with one player at each stage – a retailer, a wholesaler and a manufacturer – is considered. The model of the chain is developed using a timed, hierarchical coloured Petri Net. Simulation and performance analysis have been performed applying software package CPN Tools.

1. INTRODUCTION

A Supply Chain (SC) includes all the participants and processes involved in the satisfaction of customer demand: transportation, storages, retailers, wholesalers, distributors and factories. A large number of participants, a variety of relations and processes, dynamics, the uncertainty and stochastics in material and information flow, and numerous managerial positions prove that Supply Chains should be considered as a complex system in which coordination is one of the key elements of management.

Very important Supply Chain processes are ordering and delivery of purchased amounts. These are multiple entangled and their disorder can lead to various unwanted effects. One of them is the so-called Bullwhip Effect in which fluctuations in orders increase as they move up the chain. In order to illustrate the SC functioning and particularly the bullwhip effect, Beer Game [10] was created at the beginning of the sixties in *Sloan School of Management, Massachusetts Institute of Technology (MIT)*.

This game simulates the SC performance with one participant per each phase and today it is being played all over the world – among students and top managers, to improve the approach to Supply Chain functioning. All the simulations led to the bullwhip effect – the participants of Supply Chain reacted inadequately to sudden changes in customer demands. However, the bullwhip effect appears in those supply chains where there is no subjectivity, i.e. in cases where decision-making rules are the same for all participants and seem to be rational. This paper presents the bullwhip effect in Supply Chain simulation via a timed hierarchical coloured Petri Net [6].

Numerous papers give examples of Petri Nets used in modeling and SC analysis. In order to analyse the potential benefit of SC management, Van der Vorst, et. al. [12] modeled the SC dynamic behavior. The authors consider SC as a business process, which is to be redesigned, and in that case many different redesign scenarios are to be tested. PN is used to support a decision-maker in choosing the best-fit scenario. The authors developed the simulation/Petri-Net modeling approach to Supply Chain analysis and demonstrated their model using a case study from the food industry. Their model uses eight different performance indicators (three cost-based indicators and five service-based indicators).

Supply Chains in food industry are also modeled in [1]. The authors propose a supply chain management of perishable items combining the TTI and Wireless technologies. The proposed futuristic SC is compared with the existing situation using simulation of Generalized Stochastic PN.

An approach to Supply Chain process management (SCPM) based on high-level Petri-nets, called XML-nets is presented in [9]. It is shown that SCPM as a whole can be improved by employing XML-nets. The major advantages of the approach are: capturing process dynamics, concurrency and parallelism of processes as well as asynchronous operations; capabilities for modeling complex objects with a hierarchical structure; exchange of intra- and inter-organizational data. The paper also shows the architecture and functions of an XML-net based prototype software tool supporting SCPM.

Computer Integrated Manufacturing Open System Architecture (CIMOSA) based process behavior rules and Object-oriented PN (OPTN) are used in [5] to model the routing structures of a typical SC process. The OPTN, which they consider, consists of two parts: an internal structure, e.g. an object (composed of state places and activity transitions) and an external structure (a set of ports places which form the interface of OPTN). The authors use P-invariant to obtain the system properties from object properties.

In [7] the authors show how a Generalized Stochastic PN bridges the gap between application formalism, like process chains, and analysis methods for concurrent systems, like PN analysis methods. A small supply chain - involving a manufacturer, one of his suppliers and a transportation company, is used to illustrate their assertion.

In paper [8] the authors propose an implementation of an incremental approach to modeling discrete events systems at the structural level of systems specification. They consider the entire system and coordinate decisions at each stage of the Supply Chain. Using the example of the Beer Game, a systematic method supports the bottom-up construction of re-usable models of supply chains in the Petri nets domain.

This paper is intended to show that Petri nets may be used for studying the bullwhip effect, and especially for experimenting on how different replenishment strategies affect the parameters of certain participants and of the entire Supply Chain. Such an application of Petri nets to Supply Chains may be very useful for the education of postgraduate students. This application requires elementary knowledge of CPN and CPN tools software [3,4] as well as the knowledge of SC functioning and the bullwhip effect phenomenon.

The paper is organized as follows: Section 2 gives the basic terms of supply chains, bullwhip effect and beer game performed with two student groups, simulating two SCs; Section 3 includes the CPN model of a simplified SC, created in CPN Tools program. The same program was used for the simulation of CPN supply chain for identical customer demands as in the already mentioned beer game; Section 4 presents simulation results.

2. BULLWHIP EFFECT IN A SUPLLY CHAIN

Supply Chain coordination functions well as long as all stages of the chain take actions that together increase total supply chain profits. Each participant (phase) of the chain should maintain its actions in a good relation to other participants and the supply chain in general and make decisions beneficial to the whole chain. If the coordination is weak or does not exist at all, a conflict of objectives appears among different participants, who try to maximize personal profits. Besides, all the relevant information for some reason can be unreachable to chain participants, or the information can get deformed in non-linear activities of some parts of chain which leads to irregular comprehension. All these lead to the so-called Bullwhip Effect resulting from information disorder within a supply chain. Different chain phases have different calculations of demand quantity, thus the longer the chain between the retailer and wholesaler the bigger the demand variation.

A retailer can realize a small variation in customers' demands as a growing trend and purchase from a wholesaler more products than he needs. Increased order at wholesalers is larger than at retailers as the wholesaler cannot regularly comprehend the increased order. As the chain grows longer the order is larger. If a retailer plans the product promotion he can increase the order. If a manufacturer comprehends the increased demand as constant growth and in the same manner makes purchases, he will face the problem of inventory surplus in the end of promoting period [2]. A variation in demands increases production expenses and expenses of the whole supply chain in an effort to deliver the ordered quantity in time. A manufacturer accomplishes demanded capacity and production but when the orders come to a former level, he remains with the surplus of capacity and inventory.

Any factor that leads to either local optimization by different stages of the supply chain or an increase in information distortion and variability within the supply chain is an obstacle to coordination. The major obstacles are[2]:

- Incentive obstacles – a situation in which incentives are offered to different stages or participants in a supply chain and focus only on the local impact of an action result in decisions that do not maximize total supply chain profits.
- Information processing obstacles – situations in which demand information is distorted as it moves between different stages of the supply chain, leading to increased variability in orders within the supply chain. Demand forecasting based on the stream of orders received from the downstream stage results in a

magnification of fluctuations in demand as we move up the supply chain from the retailer to the manufacturer.

- Operational obstacles – actions taken in the course of placing and filling orders that lead to an increase in variability.
  - When a firm places orders in lot sizes that are much larger than the lot sizes in which demand arises, variability of orders is magnified up the supply chain.
  - The bullwhip effect is magnified if replenishment lead times between stages are long
  - A situation in which a high-demand product is in short supply often arises within the supply chain. Rationing schemes that allocate limited production in proportion to the orders placed by retailers lead to a magnification of the bullwhip effect.
- Pricing obstacles – situations in which the pricing policies for a product (lot size – based quantity discounts, price fluctuations) lead to an increase in variability of orders placed.
- Behavioral obstacles – problems in learning within organizations that contribute to the bullwhip effect. These problems are related to the way the supply chain is structured and the communication between different stages.

The bullwhip effect [2]:

- Increases the level of inventory, accordingly the warehouse space is more occupied, all of which leads to an increase in holding or carrying costs of storage services;
- Prolongs the lead time – the time period from the moment of purchasing to the moment of receiving the order;
- Demands more efficient transportation to satisfy the increased demand, which leads to a high transportation cost;
- Increases labor costs;
- Decreases the level of product availability, which can lead to deficiency of retail inventory;
- Causes problems in each phase disturbing relations within a supply chain since participants' efforts do not have a positive outcome – leads to distrust among participants.

2.1. BEER GAME

Originally, the game was created as a board game that demonstrates beer production and distribution, as shown in Figure 1.

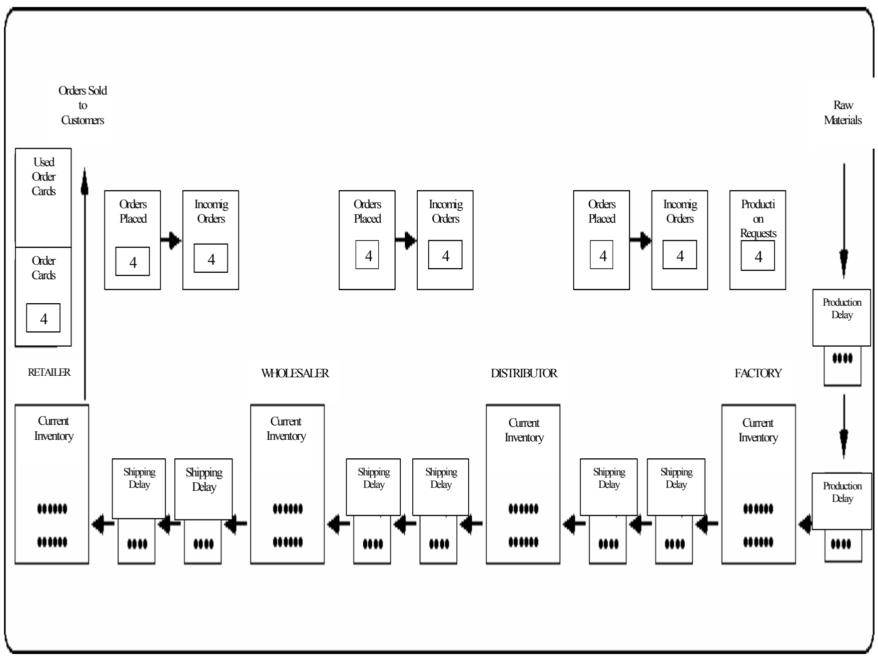

Fig. 1. Beer Game board, showing initial conditions [10]

Teams play a game whose objective is to minimize the expenses of an overall supply chain. The winner is the team with the lowest expenses. Each participant must initially invest $1, whereas the winner takes the whole investment. Teams are divided into four sectors: Retailer, Wholesaler, Distributor and Factory. One or two persons direct over each of the sectors. Coins represent beer cases, and a deck of cards is customer's demand. A customer comes to a retailer to buy a beer. The retailer meets customer's needs selling the beer from his inventory. Each incomplete order is the backorder in the following period. The retailer makes orders at the wholesaler that meets the demand from his inventory. The wholesaler purchases orders from a distributor, a distributor from a factory and the factory purchases raw materials from a supplier. The ordered products displace through an introduction phase and a transport phase, and two time units (two iteration simulations) are the period for which the product is moved from one phase to the other. Storage expenses are $0.50 per week, and the expenses incurred for a week in backorder are $1 per case.

The game start is equal for all: each participant has the inventory of 12 beer cases, and initial demand in each phase is 4 cases. In the course of several weeks, players learn the mechanisms of purchasing, to deposit inventory etc., and during that period the demand is constant – 4 cases per week. During the first three weeks, the players can order only 4 cases per week, which is logical since the demand is also 4 cases. In the beginning of the fourth week a player can order as much as he wants, and he is said that a customer's demand can vary. One of his tasks is to foresee the demand, according to what he makes orders, bearing in mind that the delivery period is two weeks. Thus, the player must foresee the demand in a two weeks' time and accordingly make an order. The game lasts for 50 simulated weeks, but the wanted effects are obvious far earlier [10].

Each player possesses good local information (about his inventory, remaining orders, receiving amounts from his direct supplier and amounts he has just delivered to the player he supplies), but he is not in possession of global information. Only the retailer knows the last customer's demand, and the others can get the information only on the demand of immediate customer. Communication between the participants is not allowed. Barriers in communication and lack of information lead to inadequate coordination in a supply chain.

The game indicated that the average expenses in MIT were about $2000, sometimes the expenses would come to $1000, but they were always higher than $1000. However, optimal expenses, calculated according to information available to players, are about $200. Each game shows the same behaviour models and reveals the bullwhip effect [10].

The beer-game was carried out with the students of specialist studies in industrial engineering, organized in cooperation by the Ecole Centrale Paris and the Faculty of Organizational Sciences at the University of Belgrade, within a course in Industrial Logistics. The students were divided into two teams, with each team representing one supply chain with four sectors: a retailer, wholesaler, distributor and manufacturer (factory). The game, developed according to the rules described above, lasted for 23 simulated weeks.

The game showed the expected results, close to the MIT's results. The total costs incurred by the first team were $3580.5 (inventory costs $2900,5, backorder costs $680) and of the second $2497.5 (inventory costs $1766,5, backorder costs $731), what is in conformity with the results obtained at the MIT. Cost distribution within teams was as follows:

- Team 1: retailer $201 (inventory $141, backorder $60), wholesaler $748.5 (inventory $545,5, backorder $203), distributor $1305 (inventory $1009, backorder $269) and manufacturer $1326 (inventory $1205, backorder $121);
- Team 2: retailer $327.5 (inventory $212.5, backorder $115), wholesaler $412 (inventory $272, backorder $140), distributor $428 (inventory $246, backorder $182) and manufacturer $1330 (inventory $1168, backorder $162).

Such results were expected – costs increase as we go from a retailer to a manufacturer.

When the students were asked to estimate the average demand, their estimation results were far higher than actual demand. Actual demands of the last-in-chain customers were the same for both teams: 4, 4, 4, 8, 10, 12, 12, 10, 8, 8, 8, 9, 8, 8, 8, 0, 0, 7, 8, 8, 8, 8, 8 cases. Such demand was selected in accordance with the beer game played at the MIT. Figure 2 shows customer demands and responding amounts of other SC participants.

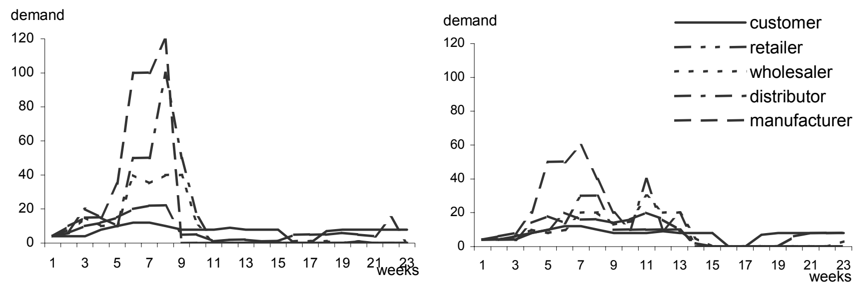

Fig. 2. Bullwhip Effect.

The left-hand side of the Figure shows the reactions by the participants of the first group and the right-hand side also shows the reactions of the participants of the first student group to specified demand. The group whose results are shown on the right-hand side took a higher risk in the game and this is why they had a lower bullwhip effect.

3. SUPPLY CHAIN MODELING USING CPN TOOLS

The primary objective of this paper is to illustrate how PN can be used in learning about and studying the bullwhip effect. Thus, the PN of a simplified SC was formed, with one participant per each phase – a retailer, wholesaler, distributor and manufacturer, and then it was simulated with CPN Tools [3,4].

The supply chain was simplified to a line of participants taking different places within a chain and making decisions according to the same rules. The two main activities of each participant are: delivery of purchased products and forming one's orders according to new orders. The selection of strategies by SC participants reduces to their decision on how they will perform these two activities. We have chosen here a simple scenario according to which all SC participants behave in the same way, i.e., they perform the mentioned activities as follows:

1. Delivery of purchased products. At the moment of receiving the order it has to be checked if the inventory stores the needed products. If the inventory shows sufficient amounts of products, the ordered, total amount is delivered. Otherwise, if the inventory amounts do not suffice it is possible either to wait for needed inventory product deposit or to deliver the incomplete inventory, with belated additional quantity. In the presented CPN the chain participants deliver even incomplete orders.

2. Forming one's orders according to new orders. Since a certain amount of products is delivered from a personal inventory, new orders are made from the next SC participant in order to keep the needed level of inventory. The decision on order quantity, in the modeled SC, is being made in the following way: if the inventory stores enough products, the same amount delivered to a customer is to be ordered, since the estimation is that the following delivery is to be of the same quantity. If the inventory shows the lack of products, the amount that could not have been delivered is to be ordered, and, as in the previous case, the amount that will suffice for the next order.

3.1. NET STRUCTURE AND DECLARATIONS

The described SC has been modeled with timed Hierarchical Coloured Petri Nets [6]. The net structure consists of five modules (pages). The top level of the model is the whole Supply Chain: a customer and the four mentioned phases, Figure 3. The three phases (participants): retailer, wholesaler, distributor and manufacturer are presented by means of substitution transitions. A sub-page models each participant. A special sub-page Manufacturer models a manufacturer, as a specific participant in the end of SC. Retailer, wholesaler and distributor are modeled by three instances of sub-page Supplier. A customer is presented by a place named customer whose initial marking represents demand in time and he directs the simulation.

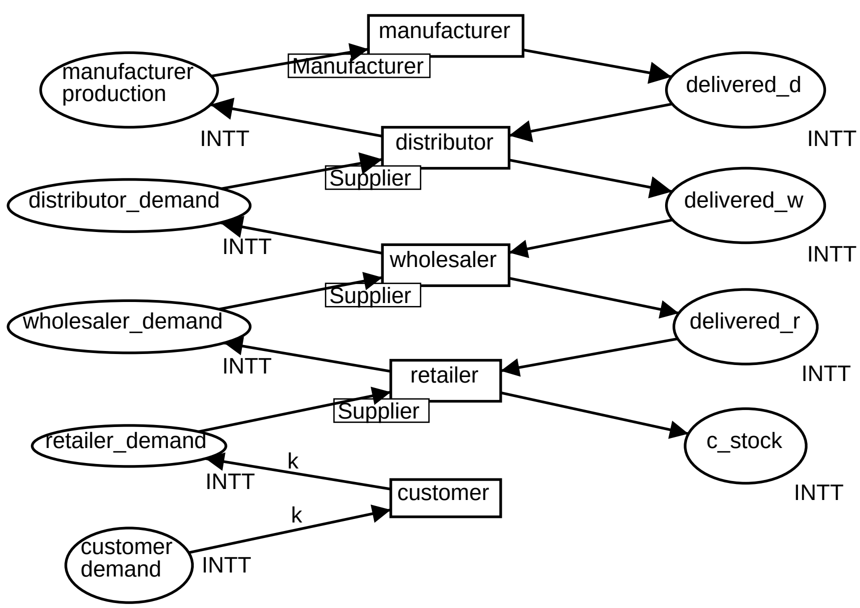

Fig. 3. Top-level Petri Net of simplified Supply Chain

It is possible to include various parameters within the SC model: prices, time, amounts of goods, a resource etc. Nevertheless, the bullwhip effect analysis requires only the follow-up on orders and deliveries in time. Figure 4 shows the declaration colour sets, variables, and function used in the net.

```
Declarations
color INT = int;
color INTT = INT timed;
var k, m, n, s: INTT;
fun rest(i,j) =if (i>=j) then i-j else 0;
fun order(i,j) = if j>=i then i else i+i-j;
val a=2;
val b=2;
```

Fig. 4. Declaration of colour sets, variables and functions

As can be seen from the declaration, to form the PN model of the SC, it is sufficient to use one standard colour set (INT) and define one timed colour set (INTT).

Function `rest(i,j)` models activity 1 described above – Delivery of purchased products. Variable i represents the order and variable j represents the inventory. The result of function `rest(i,j)` is the amount of ordered product which is not delivered. If the inventory shows sufficient amounts of products, the total amount is delivered and function `rest(i,j)` results in 0.

Function `order(i,j)` models activity 2 – Forming one's orders according to new orders. Variables i and j represent a received order and the inventory, respectively. Function `order(i,j)` behaves as follows: if the inventory stores enough products, the amount `i` will be ordered; if the inventory shows the lack of products, the amount that could not have been delivered (`i-j`) is to be ordered, and, as in the previous case, the amount `i` that will suffice the next order.

Values (constants) a and b refer to the duration of delivery and production periods. The SC is modeled by timed CPN. This simplified SC suggests creating immediate personal orders, whereas the production and delivery procedures last.

3.2. SUB-PAGE SUPPLIER

A sub-page Supplier, described in Figure 5, was used to model the retailer, wholesaler and distributor, each with one of its instances. It became possible to include more suppliers between the customer and factory. Each of them would be modeled by one instance of sub-page supplier. This was possible as the assumption of modeled SC was that each of the participants makes decisions according to the same rules. If we wish each SC participant's behaviour to be different from others', we have to form a new Subpage for each of them (or, at least, for those whose behaviour is different).

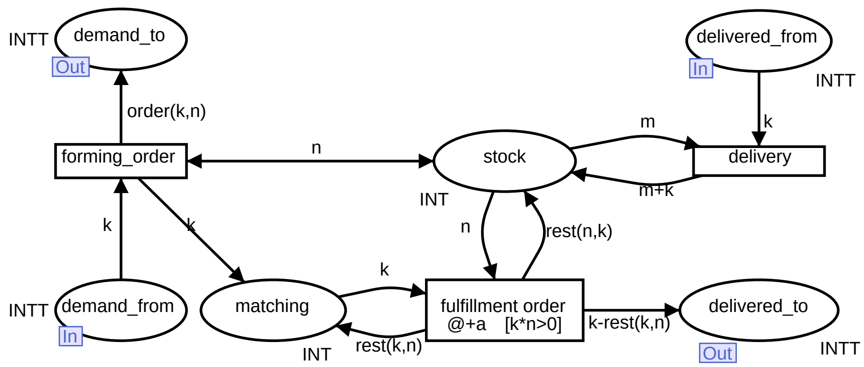

Fig. 5. Sub-page Supplier

According to the receiving order in place demand_from and inventory status in place stock, a supplier makes his own order (the second of the two basic activities), which has been modeled by transition forming_order and the function order (i,j), shown in Figure 4. The starting assumption was that forming one's order is performed much faster than the remaining activities in the SC, so the transition forming_order is momentary

Transition fulfillment_order models the first basic activity of SC participants: delivery of a needed. amount. Here, the inventory amounts are compared to the order quantity, and a decision on a delivery amount is to be made. If the inventory stores enough goods the value of function rest (k,n) (see Figure 4) will be 0, and of the function rest (n,k) = n-k. Thus, a token, which corresponds to the order quantity, will appear in the place delivered_to, the inventory will be reduced by k, and there will be no backorders. If the inventory goods are insufficient, the value of function rest (n,k) will be 0, and of the function rest (k,n) = k-n. A token n (total inventory goods) will appear in the place delivered_to, the inventory state will be 0, and a token k-n, modeling the quantity of undelivered goods, will appear in the place matching. The duration of transition fulfillment_order is (@+a), because, according to the rules of the game played at the MIT, product delivery lasts 2 weeks. It can be seen from Figure 4 that a=2. A guard function [k*n>0] in the transition ensures this transition to occur only when an order exists and when there are products in stock.

3.3. SUB-PAGE MANUFACTURER

A manufacturer is modeled by a sub-page Manufacturer (Figure 6). He decides, according to received orders and his inventory state, what quantity of goods to deliver. He is the last SC link and, in a way, he acts in the same way as suppliers, with a difference that instead of making an order for the next chain participant, he decides what amounts to produce in the following period. This was modeled by the transition manufacturing. As the production and delivery were assumed to last 2 weeks each, duration (@+b) was assigned to this transition. It can be seen from Figure 4 that b=2.

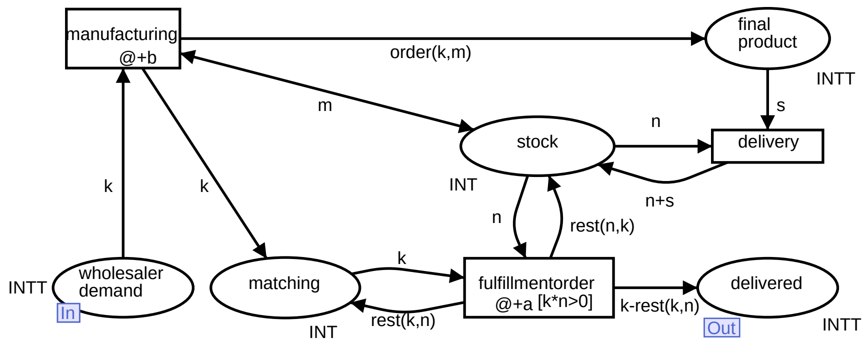

Fig. 6. Sub-page Manufacturer

Other transitions and places of this sub-page are analogous to the transitions and places of the sub-page Supplier.

4. SIMULATION RESULTS

A CPN formed in this way may be used for various experiments. It is possible to simulate different strategies of delivery and forming one's inventories and then analyze the bullwhip effect they cause. This may be accomplished by simply defining functions `rest(i,j)` and `order(i,j)` so as to model a selected strategy. It is also possible to add stochastic behaviour to a CPN in the sense of defining functions as stochastic or defining a stochastic duration of activities and transitions.

Instead of making this type of experiments, we will show here the effect obtained when simulating the demand described in 2.1 using the CPN described in section 3 as well as all the information obtainable from a simulation report. Simulation starts from the assumption that the initial system state was stable and remained stable for a certain time period and that a sudden increase in demand occurred after that. Since it is possible to compare simulation results, the initial net marking models the next state, the same state as in the beer-game with students:

- Retailer, wholesaler, distributor and manufacturer, each of them initially has 4 units of an inventory product, after the first week each has 4 units, and after the second week 4 units, which relates to the following initial marking:

1`4	in places stock@Supplier (all instances)
1`4@+1++1`4@+2	in places delivered_from@Supplier (all instances)
1`4@+1++1`4@+2	in place final product@Manufacturer

- A customer orders products once a week. Customer's demand in the first 3 weeks is 4 units per week, during the following weeks it is growing: 8, 10, 12, 12, 10, 8, 8, 8, 9, 8, 8, 8, 0, 0, 7, and in the last five weeks it is stabilized at 8 product units, which relates to the initial marking:

  1`4@+0 ++ 1`4@+1 ++ 1`4@+2 ++ 1`8@+3 ++ 1`10@+4 ++ 1`12@+5 ++ 1`12@+6 ++ 1`10@+7 ++ 1`8@+8 ++ 1`8@+9 ++ 1`8@+10 ++ 1`9@+11 ++ 1`8@+12 ++ 1`8@+13 ++ 1`8@+14 ++ 1`0@+15 ++ 1`0@+16 ++ 1`7@+171 ++ 1`8@+18 ++ 1`8@+19 ++ 1`8@+20 ++ 1`8@+21 ++ 1`8@+22 in place customer@Top page

Various chain performances can be obtained by simulation of CPN models. Figure 7 demonstrates the bullwhip effect, i.e. the reactions of retailer, wholesaler, distributor and manufacturer to customer demand.

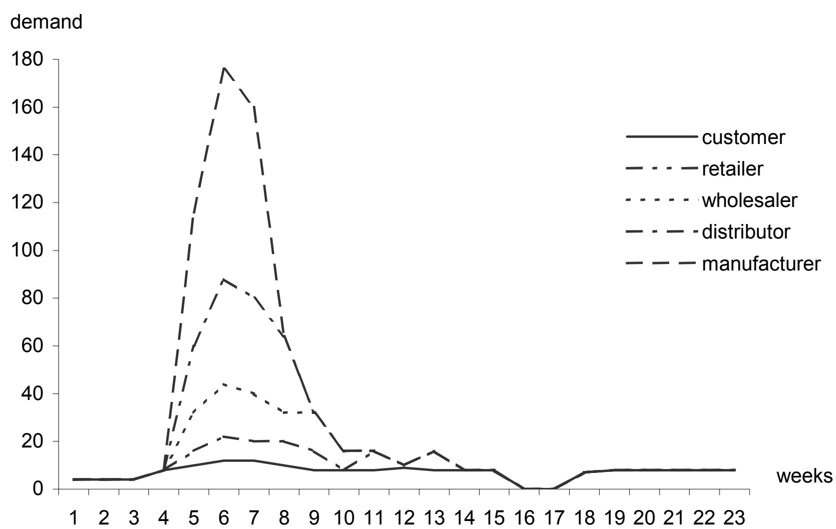

Fig. 7. Customer demand within Supply Chain – Bullwhip Effect

An expected result was obtained, close to the MIT's results. Each participant in the chain reacted inadequately and the most drastic result was recorded with the manufacturer – the last SC participant. Such behaviour is predetermined by function `order(i,j)` and some more sophisticated strategy would certainly have given beter results. This can be noted through a comparison with the results obtained in simulations with the students.

Figure 7 demonstrates a stronger bullwhip effect than Figure 2, than it was the case of students whose decisions were often very risky.

Simulation results demonstrate the consequence of bullwhip effect – inventory increase in the chain. Figure 8 shows the course of inventory state during the period of 23 weeks.

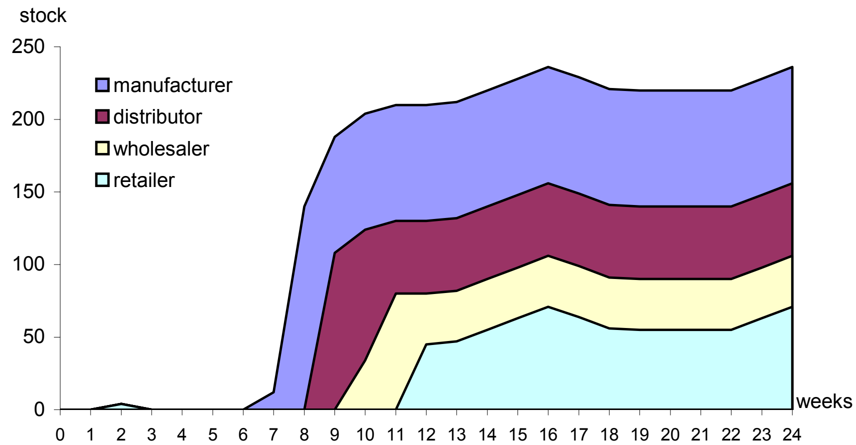

Fig. 8. The quantity of inventory goods in time

Figure 8 shows the course of backorder during the same period of 23 weeks.

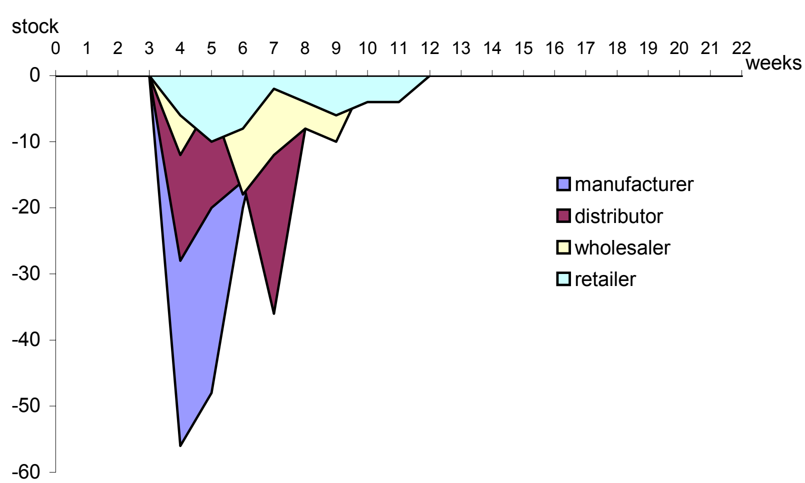

Fig. 9. Backorder in time

Using cost values from Section 2.1.: storage expenses -- $0.50 per week, and the expenses for a week in backorder - $1 per case, it is possible to calculate SC costs which represent the main indicator of chain functioning. The costs incurred by each participant and the costs of the entire SC are presented in Table 1.

Table 1

	retailer	wholesaler	distributor	manufacturer	SC
inventory cost	379,5	664	1113	1829	3985,5
backorder cost	44	64	108	124	340
total cost	423,5	728	1221	1953	**4325,5**

Simulations revealed one more phenomenon. Each chain participant has inventory goods surplus after 23 weeks. By analyzing the model, one could conclude that the results of all simulations have to be the same. However, it can be seen in Figure 10 that simulation results vary from one simulation to another. Figure 10 describes the variation in inventory goods surplus by the end of observation period. Here are the results of 20 successive simulations of the same initial marking, i.e. the same demand.

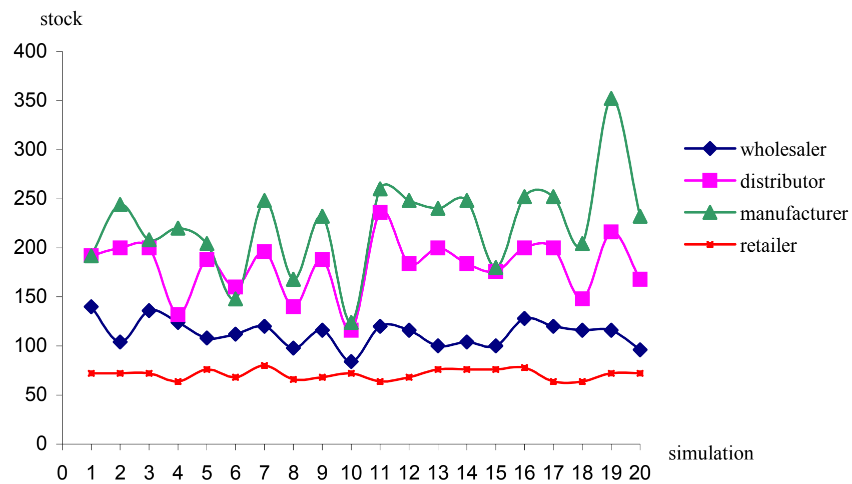

Fig. 10. Inventory goods surplus after 23 weeks in 20 successive simulations

Different results are obtained for the following reason: during the simulation, several transitions occur at the same time instant and the sequence of their occurrence affects the values tokens may take. For example, in the Sub-page Supplier, the following transitions may occur at the same time instant: forming_order, fulfillment_order and delivery. However, these transitions will not occur literally simultaneously, but in some random sequence. The quantity of supplier's order, which is determined by the occurrence of transition forming_order and which affects directly an inventory goods surplus, depends on a received order (token k) and inventory status in place sctock (token n). Each occurrence of transition delivery increases the inventory status, while each occurrence of transition fulfillment_order decreases it. This means that a different sequence of occurrences of the transitions: forming_order, fulfillment_order and delivery results in a different supplier's order.

5. CONCLUDING REMARKS

The paper describes how a Supply Chain can be modeled and analysed by CPN and CPN Tools. The CPN Tools package permits the functions of forming one's orders and delivery to be defined in an easy and fast way, which is not possible by using the modeling tools known to the authors. According to the results, the simulations can measure different performances: reactions of participants to sudden changes in customer demands (the bullwhip effect), changes in supply level in a time, surplus of inventory goods, the costs of SC participants and of the entire SC, etc. It has been shown that it is possible to form a PN model of a Supply Chain which allows easy experimenting with different scenarios, i.e., different strategies of SC participants. Unlike other beer-game implementations, where one participant must be engaged for each stage, here one participant may simultaneously experiment with the strategies of all SC stages. With CPN, the phenomena, corresponding to a real situation, e.g. a random time delivery and different decision rules in phases, as well as several participants in each SC stage can be applied to CPN model. The bullwhip effect in the non-linear SC is of special interest.

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