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Interactive Simulator of Complex Supply-chain Dynamics with Customer Preference Feedback

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ABSTRACT

The interactive simulator Distributed Logistic Simulation (DLS) capable of interaction with human actors is presented. The tool can be used to train teams of logistic operators and/or to analyze and optimize the performance of existing supply chains. The system is modularized in elementary blocks representing stations that can be combined in multiple configurations to cover a wide range of supply chain scenarios. A model of final market demand is introduced which is guided by an algorithm of customer preferences. Scenarios of two stations in parallel and in series are analyzed to demonstrate the simulator capabilities.

Key words: Interactive simulator, distributed simulation, supply-chain dynamics, customers preference feedback, demand modeling, supply chain management

INTRODUCTION

A typical rule of modern economy is that companies do not compete isolated but are integrated in business chains. The management of the relationships throughout these chains is what is referred as Supply-chain Management (SCM). "SCM involves the integration of key business processes from end users through original suppliers providing products, services and information that add value for customers and other stakeholders" (Lambert *et al.*, 1998). These processes can be inside or outside the limits of single companies, making management even more complex. The understanding of this dynamic interaction and the mechanisms of integration is a key element for the creation of value.

In this context, simulation arises as an interesting tool for analyzing supply-chain problems. Ingalls (1998) identified a set of advantages and disadvantages of simulation in SCM. Hennessee (1998) stressed the importance of simulation in the continuous redesigning of supply chains, enabling decision makers to consistently explore customer and value driven options and scenarios. In fact, many scholars have concluded that simulation is one of the best means to analyze supply chains (Schunk and Plott, 2000; Jain *et al.*, 2001; Lee *et al.*, 2002).

Chang and Makatsoris (2001) synthesize the following benefits of simulation applied to supply chains:

- It assists the analysts in capturing the main mechanisms behind the system dynamics
- Unexpected events can be modeled and tested to understand the impact on the supply chain without risking actual economic losses
- The overall supply chain processes can be easily visualized by means of graphic animation

The prolific literature related to supply chain simulation was reviewed by Terzi and Cavalieri (2004), who assessed about 80 articles published between 1989 and 2002. Calderon and Lario (2007) complementarily reviewed 40 articles from 2000 and 2006. In general, most of the models use discrete-event methods for dynamic simulation and optimization-based methods for static assessments (Ingalls, 2001).

From the point of view of programming, the simulation of dynamic systems can be implemented according to two structural approaches:

- Local simulation which uses a single model executed on one server for all nodes
- Distributed simulation which implements one model per node and can be executed on multiple servers in parallel in one cooperative simulation

In logistics, the predominant approach is the local simulation, primarily because companies do not want to share their information and simulation models with other companies within the supply chain (Terzi and Cavalieri, 2004; Calderon and Lario, 2007).

However, this vision is indefectibly changing since buyer-supplier relationship has become the most powerful process of consumer satisfaction (Kubde, 2012) and information visibility is often seen as a critical element in maintaining an efficient supply chain. Omar *et al.* (2006) defined Information visibility within the supply chain as the process of sharing critical data required to manage the flow of products, services and information in real time between suppliers and customers (Omar *et al.*, 2006).

Increasing attention is being paid to the modeling of distributed supply chains, particularly for recreating multi-company environments and interaction with human actions. It should be mentioned, though, that these kind of simulators are still in the evaluation stage; the main issue being the robustness under synchronization conflicts (Calderon and Lario, 2007).

The most popular simulation game of supply chains is the “Beer Game”, developed in the 60’s at MIT (Sterman, 1989). The goal of this game is testing strategies to coordinate the actions of warehouses and suppliers in order to comply with overall criteria of efficiency. Currently, there are several logistic and production simulators that can be executed through the Internet, where the participants play the roles of producers and logistic operators. Chen (1999) extended the Beer Game to distributed supply chains with stochastic demand. In the Hulia game (Kumar *et al.*, 2007) the players should determine the strategies in multiple level chains. There are also specific simulators: Trading Agent Competition (Arunachalam and Sadeh, 2005) simulating the production and distribution of personal computers, Logi Game that for bicycles or beer brewing automates (Thorsteinsson, 1995) and the Lean Leap Logistics Game (Holweg and Bicheno, 2002) that simulates logistics in the automotive industry.

In this article the interactive simulator DLS (Distributed Logistic Simulation) is presented, capable of interaction with human actors. The simulator can be used to train teams of operators of specific chains and/or to analyze and optimize existing supply chain scenarios. The system is modularized in elementary blocks representing stations consisting of a Warehouse (W) and a Picking Zone Operator (PZO) that can be combined in multiple configurations to cover a wide range of situations. The simulator includes a model of customer preferences that takes into account the posted prices as well as the service level of the retailers.

DESCRIPTION OF THE MODEL

DLS is an information system with independent components that communicate with each other via messages. There are two basic components that can be combined to configure distribution chains linking the primary production to the final customers, namely:

- **Picking zone operator (PZO):** Interactive node where a user serves the customer orders
- **Warehouse (W):** Interactive node where a user manages the product stocks

In a given scenario, several PZOs and Ws can coexist playing the role of basic bricks that compose a supply chain and execute on different work stations.

Besides the PZO and W components there are two additional components that communicate within the supply chains: the factories and the market. The control of the latter is not managed by the users in charge of PZO or W components but by an administrator object that dynamically provides boundary conditions upstream and downstream of the supply chain according to pre-defined strategies.

All DLS components interact through messages sent through the administrator object. The types of messages between components are:

- **Orders:** Used when components require something from each another, e.g., an order of products
- **Responses:** Information related to previous orders, *e.g.* an order satisfaction report, an order rejection, etc.

The flow of messages is synchronized by the administrator object and always begins with the demand imposed by the market which is introduced in the supply chain through the PZO acting as retailers. Every PZO imposes strategies by generating orders to its correspondent W. The latter, in turn, determine the orders and delivery strategy to the PZO acting as wholesalers and so on. Finally, when the market orders reach the factory, this component reacts by sending products to fill the warehouses of the chain, following a dynamic imposed by the administrator. In addition, the administrator imposes restrictions on the messages between PZO and W components, like delays, costs, etc.

DESCRIPTION OF THE MODULES

Picking zone operator (PZO): Each PZO station is in charge of setting appropriate strategies in order to comply with the orders coming from its client stations which can be other PZO, a warehouse or the market. There are two strategies that assign priority of delivery according to first-in-first-out (FIFO) or first-due-first-out (FDFO) criteria.

The delivery of the orders is performed by a number of employees (operators) controlled by the PZO. In addition, the PZO can establish the allocation procedure:

- One operator per order
- One operator per product. In this case, the requests from different orders corresponding to a same product are delivered only when a minimum amount is accumulated

Warehouse component (W): Each Warehouse module is in charge of setting strategies in order to manage its stock balancing the costs and the service level. The strategy is defined by the following parameters:

- Order specifications to the supplier: Replenishment quantity (units per product) and selected transportation
- Safety stock of each product
- Storage location of each product (each zone has different retrieval time and storage cost)

The warehouse gets an order message each time an operator requests a delivery of a batch of products. For every product in the order, the simulator checks if the stock is sufficient and if so, the requested amount is reduced from the stock level of the corresponding products at the corresponding warehouse. The orders response dynamics is determined by the administrator configuration parameters and the stock location and shortages which can eventually bring about waiting queues.

Factory component: The response of the factories to the orders from the primary suppliers is simulated with a module that generates delays in the availability of products according to statistical parameters established by the administrator.

Market component: The demand is generated in the market component with a probability distribution set by the administrator which its statistical parameters can be changed during the simulation at any time, then the market component generates the orders through a model of consumers preferences based on prices and the history of service level of the retailers. The demand model assigns the orders to the PZOs retailers guided by a probability distribution constructed by normalized weights w_i associated to each retailer i as:

$$w_i = T_i / p_i \Big/ \sum_{i=1}^{\#PZO} T_i / p_i \tag{1}$$

where, p_i is the price posted by the retailer for the order (weighted average of the prices of all products of the order) and T_i is a “trust” parameter that ranks the service level of the retailer-i according to its past performance. The latter is actualized after every delivery as follows:

$$T_i^{new} = T_i^{old} \, e^{d(\bar{\tau}-\tau_i)} \tag{2}$$

where, τ_i is the last delivery time of retailer i, $\bar{\tau}$ is the historical average of all orders and retailers and d is a discount rate that controls the relative value of the service respect to the prices. It can be seen that the trust of the perfect retailer ($\tau_i = 0$) will increase with every delivery, the trust of the average retailer ($\tau_i > \bar{\tau}$) is always constant and the trust of mediocre retailers ($\tau_i > \bar{\tau}$) will decrease with every delivery.

CONFIGURATION OF SCENARIOS

The modularization of DLS provides a powerful tool to configure a large variety of supply-chain networks using a user-friendly graphical interface. The main features that can be configured in each component are the following:

Consumer market:

- Probability distribution of the demand
- Trust penalty per unit of delivery time
- Initial value of the trust parameter

Factories:

- Primary product prices
- Maximum capacity of each transportation mean
- Number of transport units available
- Fixed and variable costs of each transportation mean
- Transport time of each transportation mean
- Lead time statistics

Warehouses:

- Financial costs of stocks
- Profit margin
- Safety stock
- Lot size per order
- Estimated demand during the lead time
- Configuration of the storage zones (capacities, costs, handling time and handling cost)

Picking zone operators:

- Wages
- Cost per dismissed worker

USER INTERFACES

DLS is based on a graphic environment that provides multiple windows to monitor the relevant variables and introduce changes in the control parameters. Figure 1 and 2 show the control-panel

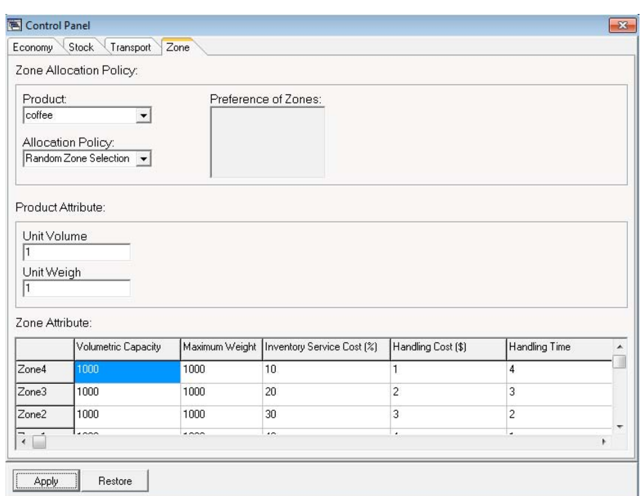

Fig. 1: Administration window of a warehouse station

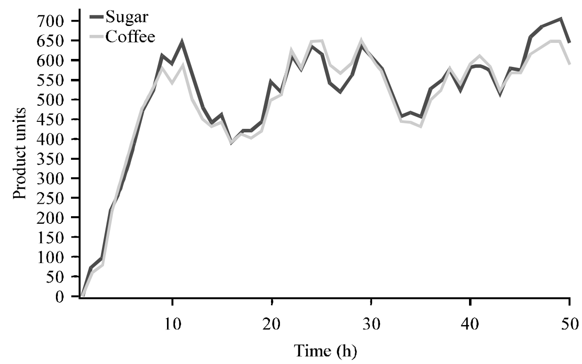

Fig. 2: Monitoring window of a warehouse displaying the waiting list of two products

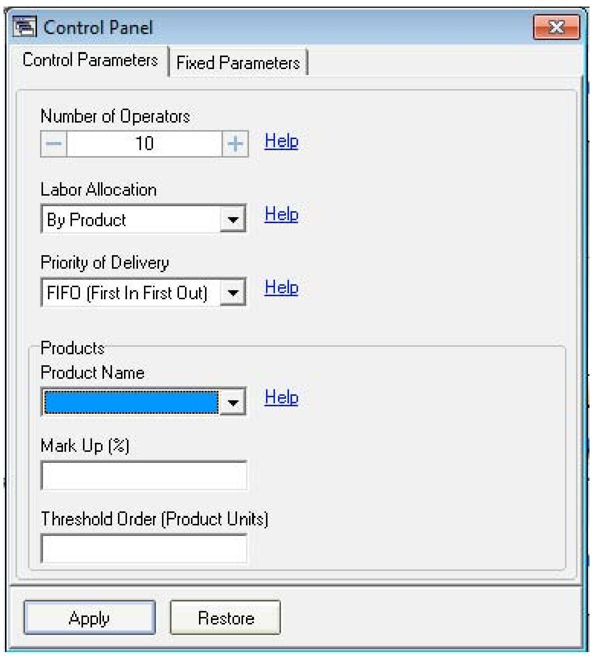

Fig. 3: Administration window of a PZO

window of a W station and the corresponding monitoring window. Figure 3 and 4 show similar interfaces of a PZO module.

The variables that can be monitored in a W station are:

- Current stock
- Storage-zone occupation
- Waiting list of products
- Average service time
- Costs and profit
- Service level

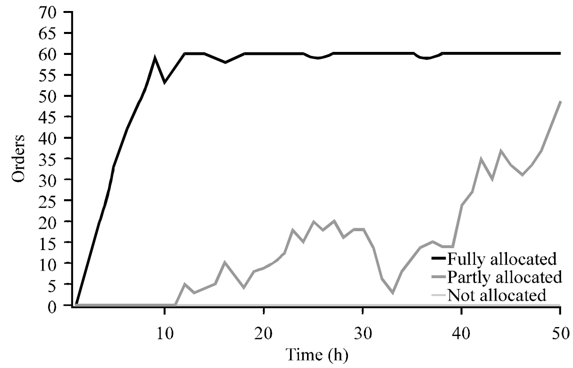

Fig. 4: Monitoring window of a PZO station displaying the state of orders

The variables that can be monitored in a PZO station are:

- Orders (orders rate and orders status)
- Labor occupation level
- Operational performance (average lead time and average deadline)
- Costs and profit

IMPLICIT INVOCATION ARCHITECTURE

The main purpose of the DLS architecture is to provide a distributed platform to support the supply chain model. To fulfill this objective, DLS uses the implicit invocation of event-based architecture (Hewitt, 1969; Craig, 1999; Sullivan and Notkin, 1990; Garlan and Shaw, 1993). The rationale behind implicit invocation is that, instead of directly invoking a procedure, each component announces events. Other components in the system register interests in events by associating procedures to them. When an event is announced the administrator module invokes all the procedures that have been registered for it. In this way implicit invocation provides strong support for reuse, since any component can be introduced into a system by simply registering it for the events of that system and flexibility, since components can be easily replaced by other components in the system.

In addition, DLS also introduces an invocation variant allowing external users to send events to a subsystem (unicast) or to all subsystems (multicast), by means of a Dispatcher component that is registered to that purpose (Fig. 5).

DLS APPLICATIONS

In order to analyze the performance of the simulator, DLS was applied to simulate two supply-chain scenarios with human actors interacting with W and PZO work stations. The first scenario is composed by two W-PZO chains competing for the distribution of two products and the second scenario is a two-level (Wholesaler-Retailer) supply chain.

Parallel supply chains: Figure 6 shows a scenario consisting of a factory supplying products that are distributed directly to the final consumers by two supply chains (labeled 1 and 2). Each chain is independent and has the basic structure of a W and its corresponding PZO. This scenario is useful to validate the model in a competitive environment, assess how the variation of certain

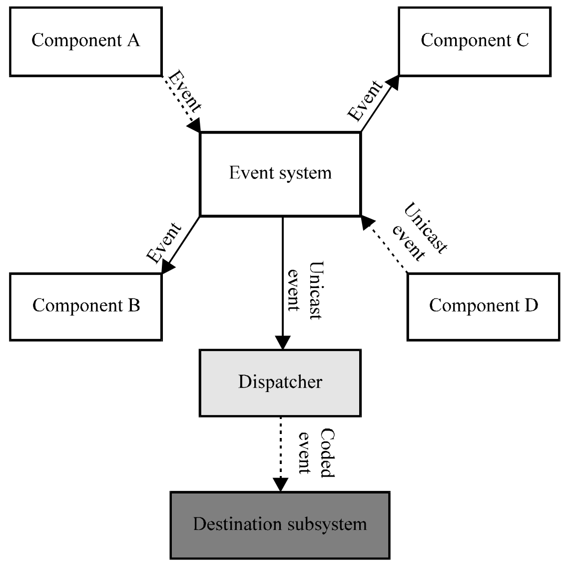

Fig. 5: Diagram of the dispatcher action

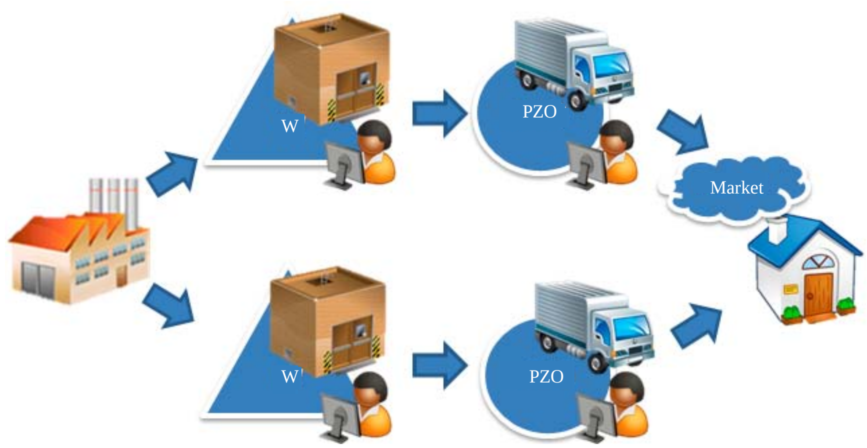

Fig. 6: Scenario of two competing chains in parallel

parameters impacts upstream and downstream of the chain and visualize how the market model operates. Both chains start with the same set of parameters. At time step 50 the number of operators and the estimated lead time of supply-chain 2 are reduced by a factor 1/2, causing an imbalance that should be compensated by appropriate changes in the control parameters.

Figure 7 shows the evolution of different indicators for each retailer. At time step 50 the service time of chain 2 begins to increase due to the reduction of its service capacity. Correspondingly, at the same time, the trust factor of chain 2, indicating the customers satisfaction, also decreases. As a consequence, PZO1 starts getting more orders from the market but since its service capacity is not prepared to meet the increasing demand, after some delay (t~120) its delivery time increases. From then on the chains oscillate in counter phase, that is, when one of them increases the delivery time the delivery time of the other decreases and so on. The oscillation period is about 60 time steps. The

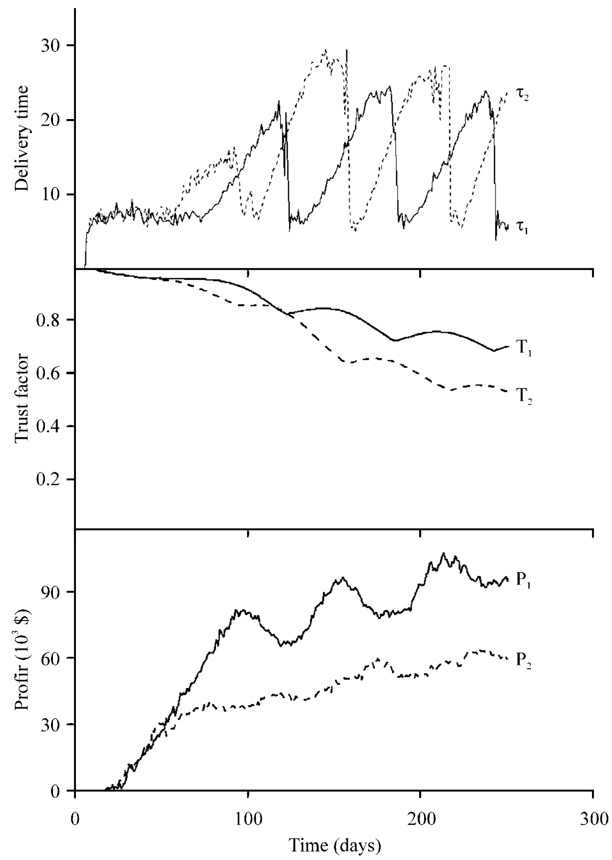

Fig. 7: Evolution of the main indicators in the parallel scenario. At t = 50 the service capacity of PZO2 drops to its half value. The discount rate in Eq. 2 is d = 0.0005

lower graphic in Fig. 7 shows the economic performance of each PZO. It can be seen that the profit of PZO1 is in general higher which is reasonable considering that its service capacity is greater than the capacity of the other retailer. However, it is interesting to note that the profits oscillations of PZO1 are much larger than PZO2 profits.

Supply chain in series: Figure 8 shows a scenario of a single supply chain consisting of a wholesaler (Ws) and retailer (R), each one defined with the basic structure of a W and its corresponding PZO. The scenario is useful to analyze logistics coordination problems similar to the Beer Game which under certain conditions leads to inventory oscillations (Sterman, 1989). The case study assumes that the warehouses take independent inventory decisions relying only on the history of orders from the neighboring players. With the assumed linear cost structure, the experiment shows that the variances of orders amplify as one move up in the supply chain (bullwhip effect). The expected behavior has the following characteristics (Sterman, 1989):

- **Oscillation:** Orders and inventories are dominated by large amplitude fluctuations
- **Amplification:** The amplitude of order rates increases from customer to retailer to factory. The peak order rate at the factory is on average more than double of the peak order rate at retail
- **Phase lag:** The further the node from the customer in the supply chain, the later the peak of the order rate

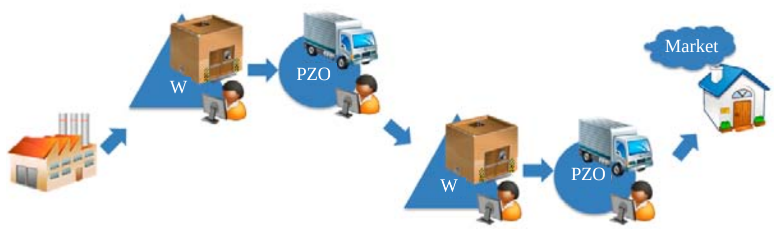

Fig. 8: Scenario of two levels supply-chain

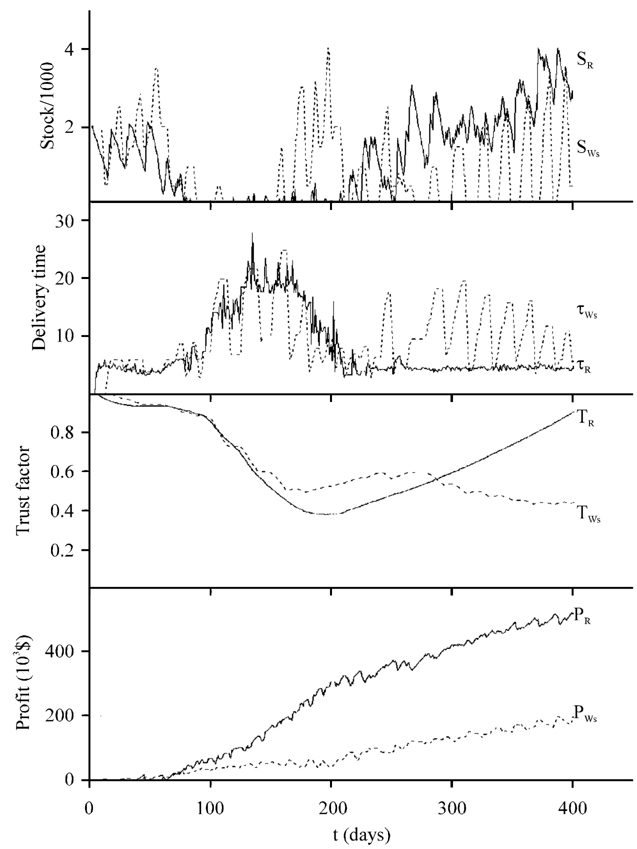

Fig. 9: Evolution of the main indicators in the scenario in series. The discount rate in Eq. 2 is d = 0.001

Figure 9 shows the evolution of the main indicators in the two-level chain controlled by a human operator in each W-PZO station. Initially both levels operate in phase responding to a stationary market demand. At time step 50 the administrator doubles the market demand without letting the operators know the change, generating a wave of orders that spreads downstream along the chain. The immediate consequence is the drop in the stocks and the increase in the average delivery time of both levels. After the operators' reaction the stocks start to recover, the primary supplier first (t~150) and later the retailer (t~200) which should wait for the former to receive products from the factory. From then on, an oscillatory behavior is established which the operators try to compensate with more or less success.

DISCUSSION

In the literature, the predominant approach in logistics simulation seems to be the local simulation. As it was exposed before, the primarily reason is because companies do not want to share information with other companies within the chains. In DLS we propose a distributed simulation approach, allowing human interaction and permitting that some specific information could be managed from a specific node without necessity of sharing it.

As noted by Calderon and Lario (2007), distributed simulation has not been the most extended approach because of synchronization issues, problem solved with the incorporation of DLS simulator and its data management technique.

In the other field of the DLS application: Education and training of supply chain management, several supply chain simulation games were developed by universities but few of them present a real competence between supply chains for the market share and a customer preference feedback. This represents from our point of view a weakness in the SCM simulation, since every supply chain is ultimately market-driven. DLS presents a customer preference model that takes into account the historical service level and the price posted by a retailer, representing a big step in the capabilities of these tools for the evaluation of the student´s performance in managing supply chains.

In conclusion, a dynamic simulator of supply chains capable of interaction with human actors was presented. The simulator can be used to train teams of operators of specific chains and/or to analyze and optimize existing supply chain scenarios. The system is modularized in elementary blocks representing stations consisting of a warehouse and a picking zone operator. A model of final market demand guided by an algorithm of customer preferences was included which takes into account prices as well as service level of each retailer. Scenarios of two stations in parallel and in series were analyzed to demonstrate the capabilities of the simulator, showing reasonable trends in response to human actions.

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