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A multi-agent system for chemical supply chain simulation and management support

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Abstract. Modern chemical production is customer-driven and the desired delivery time for the products is often shorter than their campaign length. In addition, the raw materials supplying time is often long. These features make it desirable to provide tools to support collaborative supply chain decision making, preferably over the Internet, and where there are conflicts, compromise decisions can be quickly reached and the effects of the decisions can be quantitatively simulated. This paper describes such a multi-agent system (MAS) that can be used to simulate the dynamic behaviour and support the management of chemical supply chains over the Internet. Geographically distributed retailers, logistics, warehouses, plants and raw material suppliers are modelled as an open and re-configurable network of co-operative agents, each performing one or more supply chain functions. Communication between agents is made through the common agent communication language KQML (knowledge query message language). At the simulation layer, the MAS allows distributed simulation of the chain behaviour dynamically, so that compromise decisions can be rapidly and quantitatively evaluated. Because in a chemical supply chain the scheduling of the plant often dominates the chain performance, an optimum scheduling system for batch plants is integrated into the MAS. The functions of the system are illustrated by reference to a case study for the supply and manufacture using a multi-purpose batch plant of paints and coatings.

Key words: Supply chain management – Supply chain simulation – Software agents – Paints and coatings

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1 Introduction

Chemical supply chains are integrated networks where a number of business entities, i.e., suppliers, manufacturers, distributors and retailers, work together to acquire raw materials, convert them into final chemical products, and deliver the products to the retailers and final customers. It is estimated that the supply chain can represent as much as 60-80% of a typical chemical manufacturer's costs, and that a 10% reduction in supply chain costs can bring a 40–50% improvement in before-tax profits (Gibson, 1998). It has also been reported that one of Du Pont's polymers businesses reduced working capital tied up in inventory from £160,000,000 to £95,000,000 (Kafoglis, 1999). Compared with other industrial sectors such as the car manufacturing industry, the chemical process industry (CPI) is thought to have lagged behind in addressing supply chain issues. Benson (1998) estimated that the typical costs of operating the supply chain in the chemical industry are about 14% of sales, compared with the world-class figure of about 6% in other industrial sectors, therefore there is a gap of 8% for improvement. Several researchers have pointed out that CPI supply chains have some specific features compared with other industrial sectors (Bodington and Shobrys, 1999), for example, the chain is often longer and the finished products co-exist with by-products in the market. The most distinguishable feature is considered to be on the engineering side, i.e., the chemical plant, because its equipment connection and configuration as well as scheduling and control schemes are not flexible and agile enough to meet the dynamic demand of the supply chain.

The overall objective of this paper is to describe a distributed and co-operative system for support of supply chain management over the Internet, and integrate the scheduling and control of the plant into the dynamics of a supply chain. The system will be used to develop a prototype system for the supply and manufacture of paints and coatings using a multi-purpose batch plant. Using the prototype system, issues related to distributed software agent design and implementation, including legacy software wrapping, conflict resolution through negotiation and optimal problem solving using well-established OR methods will also be explored.

The rest of the paper is organised as follows. In Section 2, a brief review of computer aided supply chain management will be given, in order to clarify the contribution of the present work. Section 3 presents the system architecture and implementation of the multi-agent supply chain system. Section 4 describes the structure of the supply chain and the production process for paints and coatings. Section 5 presents the simulation considerations for each agent. Sections 6 and 7 discuss the use of the system for communication and negotiation for conflict resolution, which are followed by discussion of some illustrative simulation results in Section 8 and concluding remarks in Section 9.

2 Previous work on supply chain studies

Previous research on computer aided supply chain management has mainly adopted three approaches. These are methods based on *control theory*, *operational research* methods such as mathematical programming, business games and statistical analysis, and *simulation* approaches.

2.1 Previous work based on control theory and operations research

Supply chain studies based on control theory make an analogy between supply chains and control systems. Towill (1997) used feedback control block diagrams to represent the supply chain, and difference equations to describe chain dynamic behaviour. These studies suggest improving chain performance through modifications of the chain such as through removal of one layer of the chain, information integration, reduction in lead-time, and modification of ordering rules as well as combinations of these. In the chemical industry, Perea-Lopez et al. (2001) also studied the control theory based methods. They proposed a model representing balances of inventories, balances of orders, shipping rates and initial and boundary conditions. Their framework was applied to a company that produces three types of polymers and supplies a distribution network composed of warehouses, distribution centres and retailers. Each site is considered as a "tank" that stores material or information. Bose and Pekny (2000) proposed the use of model predictive control for planning and scheduling of a generic supply chain. They also studied the effect of varying co-ordination structures and other parameters on the overall customer service level.

Supply chain optimisation can be roughly clustered into three groups. The first group is concerned with multi-echelon inventory systems and focuses research on cost and service optimisation of warehousing policies at different levels of a supply chain. In turn, these may use a decentralised view (when ordering is triggered solely by inventory position at each stock-point, or *installation stock policy*) or a centralised view. The latter is called *echelon stock policy* and in this case ordering is triggered by the echelon inventory position, that is, the sum of all stock in transit to this stock-point plus its physical stock plus that in transit to or on hand at its downstream stock-points minus back orders at its end stock-points. The literature related to multi-echelon optimisation is abundant nowadays mainly due to the increased ease of exchange of product information between supply chain components (Sherbrooke, 1968). A literature review of optimal multi-echelon problems from a service level perspective was given by Diks et al. (1996). Most work dealt with one distribution centre and N retailers (e.g. Axsater and Zhang, 1999; Cachon and Zipkin, 1999; Seo et al., 2002; Svoronos and Zipkin, 1988). Tempelmeier (2000) developed a procedure for estimating the probability distribution of the order waiting time in a discrete time periodic (s, S)-inventory system, which is particularly useful for determination of inventory location that serves downstream nodes (e.g. production processes, regional warehouses or customers) in a supply chain. Among these papers, very few deal with optimal solution methods for systems of more than two-echelons, apart from the work of Diks and de Kok (1998, 1999) who developed a model for divergent multi-echelon systems and tested it using a decomposition approach. Van der Heijden et al. (1999) presented a method for multi-echelon divergent systems with stochastic lead times, which computes the order-up-to level and the allocation fractions required to achieve given target fill rates.

The second group includes mainly those that use classic operations research methods and consider more than one of the following aspects of supply chain management: plant design, production scheduling, logistics of distribution and inventory management (e.g., Chandra and Fisher, 1994; Haq et al., 1991; Van Roy, 1989). General literature reviews have been made by Thomas and Griffin (1996) and Maloni and Benton (1997). The review by Vidal and Goetschalckx (1997) paid special attention to mixed-integer programming models of production-distribution problems. Baita et al. (1998) reviewed dynamic routing and inventory problems. The majority of works on chemical industries' supply chain optimisation also belong to this group. Bok et al. (2000) proposed a multi-period optimisation model that considers inventory profiles, process operating modes and product sales. Zhou et al. (2000) used goal programming to optimise a continuous chemical plant with a multi-objective function. Gjerdrum et al. (2001) modelled multi-enterprise supply chains assuming fair profit distribution as a mixed-integer non-linear program. Timpe and Kallrath (2000) modelled a chemical supply chain considering production and distribution using a MILP approach. Kallrath (2002) presented a comprehensive review of literature on planning and scheduling of batch and continuous process plants. Other works studied sub-optimal solutions using commonly applied policies, as for example Agrawal and Cohen (2001), who analysed the effect of a fair share policy in a production-inventory problem over service level. An interesting method for coordinating information and materials flows in a supply chain using optimisation models was presented by Haehling von Lanzenauer and Pilz-Glombik (2002) and applied to a modified version of MIT's Beer Distribution Game. It demonstrated enormous potential for performance improvement using analytical decision support over human decision making. In chemical supply chains, optimisation using mathematical programming is probably the most widely studied approach. However, this approach also has some limitations. For example, as indicated by Kafoglis (1999), it is technically insufficient in handling a high volume of what-if scenarios, and it is very difficult to solve a problem where more than two management issues are considered. Based on the study of networked batch plants with interdependent production schedules, multi-stage production at multi-purpose facilities and chain production, Berning et al. (2002) also addressed the insufficiency of pure mathematical models for scheduling and proposed an integrated framework that consists of three layers, i.e. an optimiser for scheduling solution, a mechanism for collaborative planning among the involved plants, and a tool for manual updates and scheme changes.

The third group includes mainly statistical analysis-based methods, where at least one of the variables is unknown and is assumed to follow a particular probability distribution. Business game models can also be assigned to this group. An example of statistical approaches is the work of Applequist et al. (2000), who presented a method for evaluating supply chain projects where significant risk exists using statistical methods. Corbett (2000) presented a two-echelon study considering incentive conflicts and information asymmetries. Gupta et al. (2000) considered demand uncertainty in a production-inventory problem and converted stochastic features of the problem into a chance constraint programming problem. Cohen and

Lee (1989) used stochastic models to represent production, inventory and distribution in the supply chain.

2.2 Previous work based on simulation and agents

Simulation approaches experiment with an executable model of the system. In most cases these models are created to support one of the previously described approaches. Research in this area dates back to 1958 with Forrester's seminal work on industrial dynamics (Forrester, 1958). We will centre our review on the application of agents as simulation tools to solve operational research problems. Agent technology has been already applied to several operations research problems. For example, Pendharkar (1999) explored design issues of a multi-agent system that uses genetic learning of job scheduling strategies. Knotts et al. (2000) solved a series of published project scheduling problems using agents. They compared results when using sets of reactive and deliberative agents and concluded that deliberative agents perform much better than purely reactive agents. In recognition of the geographical nature of a supply chain, most recent work on simulation of supply chain behaviour has centred on developing distributed systems (Parunak et al., 1999), and some used agent technology (Gjerdrum et al., 2000; García-Flores and Wang, 2000). The method models the dynamics of individual components as well as the emergent interacting behaviour. Since it mimics the natural structure of a supply chain and interacting mechanism, it has the advantage of being able to be easily reconfigured when the chain structure is reorganised.

Other researchers (Fox et al., 2000) have also studied agents as a technique to develop co-operative supply chain systems. Their work incorporates the three levels of decision making: *strategic*, e.g. where to allocate production, or what is the best sourcing strategy, *tactical*, that is, forecasting, scheduling, ordering of short lead materials and *operational*, that refers to inventory deployment and detailed scheduling. In a parallel study, Chen et al. (1999) studied the negotiation methods using agents in supply chain management. Swaminathan et al. (1998) presented a sophisticated framework of a supply chain modelling library which is composed of agents (classified as production and transportation), its control elements (classified as flow, inventory, demand, supply and information) and their interaction protocols. In their work, three message classes were implemented including money, information and materials. These components are exemplified after analysing different real supply chains.

Compared with the many efforts on control theory and optimisation based methods for supply chain support, the work on agent based systems is still very limited, especially those dedicated to the chemical industries. The publications on agent based supply chain systems have either focused on co-operative decision support or distributed simulation, none has simultaneously addressed both. The current study is aimed at developing a multi-agent based system for co-operative decision support over the Internet as well as distributed simulation of chain behaviour, for chemical industries' supply chains. Agent based technique has a number of distinctive features (Jennings and Wooldridge, 1999; Han et al., 2000; Batres et al., 1997; McGreavy et al., 1995), making it attractive for developing this project. First, agents constitute a very effective technique for designing distributed supply chain systems over the Internet. This is very important considering the fact the chain components are actually geographically distributed. In addition, agents mimic the supply chain structure, i.e., systems for individual chain components can be developed and maintained independently and the overall system behaviour and decision making is through interactions of the subsystems. Such a system can be easily maintained. It also offers the advantage of being re-configurable when necessary. Furthermore, it is easy to develop such framework as an open system, i.e., new tools can be easily incorporated into it without major changes in the rest of the structure.

3 The multi-agent system and its implementation

3.1 Agent structure for supply chain modelling

A software agent is an encapsulated computer program that possesses some properties, most importantly, communication for the purpose of co-operation and negotiation, learning to improve performance over time, and autonomy implying that agents can act pro-actively over their environment rather than passively waiting for commands (Jennings and Wooldridge, 1999). These properties make agents different to traditional standalone software systems. Software agents have proved to be a useful technique in designing distributed and co-operative systems in many industrial and business sectors, including telecommunication, air traffic control, traffic and transportation management, entertainment and medical care (Jennings et al., 1998). They have also been used for developing distributed systems that can collaboratively solve domain problems over the Internet. Agent-based systems are difficult to build and debug from scratch. Therefore it is important to use agent building tools, such as IBM Aglets Software Development Kit (also known as Aglets Workbench), JAFMAS (Jave-based Agent Framework for Multi-agent Systems) (Chauhan, 1997), and JATlite (Java Agent Template Lite).

It is important to note that the agent paradigm fits better the real structure of a supply chain, where different entities are in charge of their own responsibilities. As members of a loosely coupled network, these entities work together to solve a problem (optimising supply chain operation) that is beyond the individual capabilities or knowledge of each component. Of course, tackling this specific problem in this way does not conflict with other aspects of supply chain management where a centralised database is desirable, as for example project management or customer information repositories for *e*-commerce.

Peng et al. (1999) studied the use of agents for designing supply chain management systems and concluded that there are three requirements that are essential:

1) *A common agent communication language (ACL) and protocol*. This is the language the agents use to exchange messages. In this work, we used the *Knowledge Query and Manipulation Language* (KQML). KQML is both a message format and a message-handling protocol to support run-time knowledge sharing among agents. KQML can be used as a language for an application program to interact with an intelligent system or for two or more intelligent systems to share knowledge in support of co-operative problem solving. KQML focuses on an extensible set of

Table 1. Examples of supply chain agent communication performatives

Performatives	Sender	Receiver	Information
Start	External agent	Purchasing	–
Order	Purchasing	RMS	–amount ordered, –due times
Advertise	RMS	Purchasing	–RM unit prices
Delivery	RMS	Plant	–delivery times
Forward	Purchasing	Logistics	–RM unit prices
forward	Plant	Warehouses	–
advertise	Logistics	Retailers	–P unit prices
Delivery	Warehouses	Retailers	–delivery times
Order	Retailers	Logistics	–amount ordered, –due times
Order	Logistics	Warehouses	–transportation plan, –amounts ordered, –due times
Order	Warehouses	Plant	–amount ordered, –due times
Delivery	Plant	Warehouses	–delivery times, –Plant operating cost, –RM demand
report–w	Warehouses	Logistics	–Warehouse op. Costs, –Plant operating cost –RM demand, –transportation costs
pay–budget	Logistics	Purchases	–
pay–budget	Purchases	Plant	–
Order	Plant	Purchases	–amount ordered, –due times
report–p	Purchases	Logistics	–
authorise	Logistics	Purchases	–
Order	Purchasing	RMS	–amount ordered, –due times

performatives, which define the permissible operations that agents may attempt on each other's knowledge base. A performative is a predicate with some parameters.

The performatives comprise a substrate to develop higher-level models of inter-agent interaction such as contract nets and negotiation. It is useful for programs to communicate attitudes about information, such as querying, stating, believing, requiring, achieving, subscribing and offering. Table 1 shows some examples of performatives used in the current system.

KQML messages are indifferent from the format of the information itself, thus KQML expressions will often contain sub-expressions, i.e. so-called ”content” languages. The only restrictions to KQML messages are that (1) expressions must be viewed as entries in a knowledge base, and (2) sentences must be encoded as ASCII strings. We have used some of the reserved performatives (Labrou and Finin, 1997) and created some new ones.

2) A *common format* for the contents of communications is necessary. Agents should be able to access a set of neutral commands. Neutrality implies that the

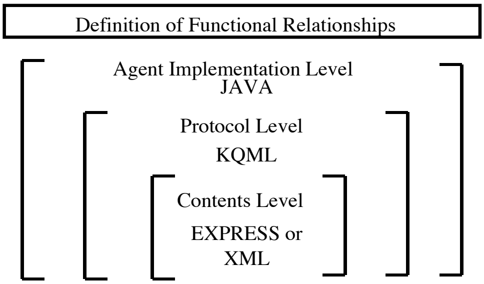

Fig. 1. Levels of implementation

contents may be used for different purposes. STEP (the STandard Exchange of Product model data) and XML (eXtensible Mark Language) are investigated as the content languages.

3) The agents also need to use *a shared ontology*. Ontology is a formal description of entities and their properties, relationships, constraints and behaviour. Ontology is a "model of the world". Agents must share the same conceptual model of the domain problem in order to understand the concepts and get effective communication, and this model of the environment is represented by the data models supported by the content language.

3.2 Agent implementation tools

The language chosen to implement the system is Java. The main reason for using Java is that it is Internet oriented and platform independent. The most important Java library for the development of this project is JATLite, a package of programs developed in Java by the Centre for Design Research of the University of Stanford. It allows users to quickly create new-layered software agents that communicate robustly over the Internet and exchange information with other agents on other computers where they are running. JATLite provides a set of Java templates and a Java agent infrastructure that makes it easy to build systems in a common way. The template for building agents uses a common high-level language and protocol and provides users with numerous pre-defined Java classes that facilitate agent construction. Figure 1 shows the language implementation levels. A useful feature of JATLite is that it can "wrap" existing and often standalone programs by providing them with a front-end that allows them automatically to communicate with other programs, sending and receiving messages and files.

The second level of implementation in our simulation uses KQML as the protocol language. KQML is the "shell" that provides information about the sender and receiver agents, the subject of the message and additional information. Finally, the innermost layer in the agent communication framework is represented by a neutral file exchange format, for which we use EXPRESS or XML.

4 The supply chain and the manufacturing process

The supply chain used as a case study is composed of six classes of agents: retailers, logistics, warehouses, purchasing departments, plants and raw material suppliers (RMS). They can also be grouped as *functional* and *information* agents. Functional agents are those through which there is a material flow (retailers, warehouses, plants and RMS), whereas information agents refer to those that support the activities of functional agents through taking decisions or facilitating certain operations (logistics and purchasing departments). Functional agents are subject to optimisation by OR methods and carry inventories of raw materials (if they are located in the supply side of the chain, i.e. RMS and plants) or finished products (if they are located in the demand side of the chain, i.e. warehouses and retailers) and are assigned a physical location. There is no material flow through information agents, so no physical locations are necessary for them. Figure 2 depicts the class relationships. The supply chain examined in this study consists of two warehouses that distribute the finished products to eight retailers spread in four countries, i.e. United Kingdom, Ireland, France and Belgium. The warehouses get the finished products from a single plant located in the UK.

The production plant is based in the UK and requires supply of three groups of raw materials (resin, paint components and packaging materials). These are supplied respectively by three RMS that are also located in the UK.

The simulation is conducted at different time scales, as can be seen in Figure 3. In the contents level, the processes that occur at the smallest time units (hours-days) are managed at the plant by the scheduling optimisation software. At the protocol level, each time step in the simulation corresponds to planning horizons of

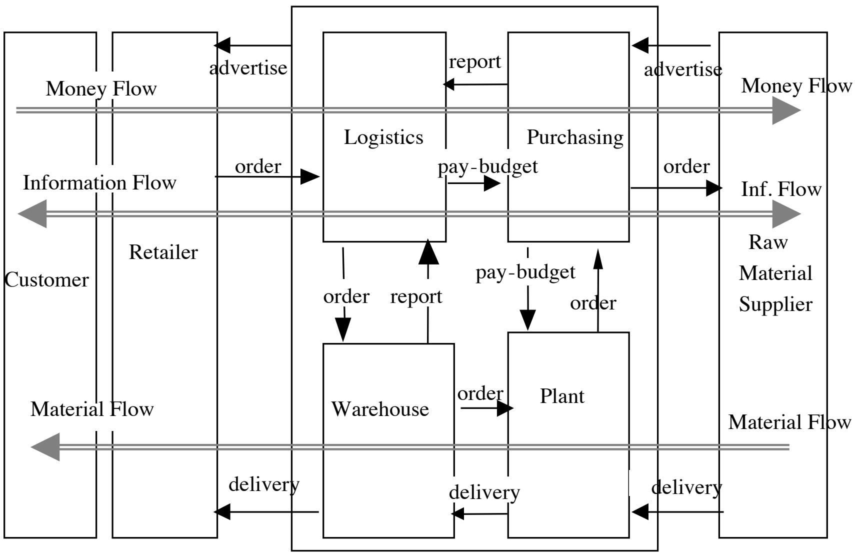

Fig. 2. The agent classes and their relationship

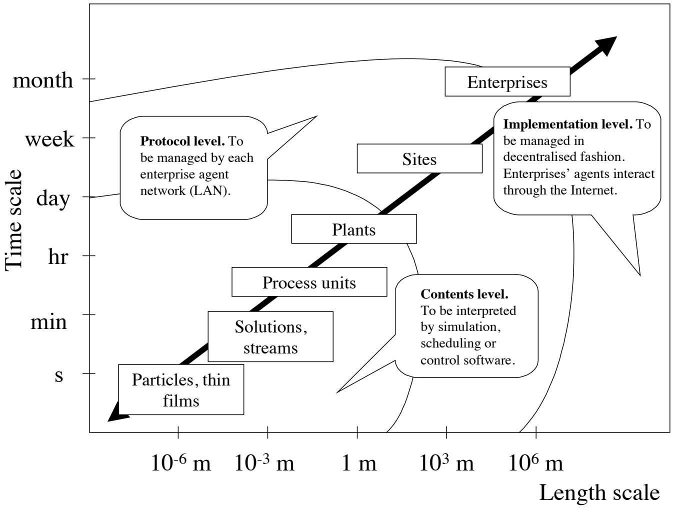

Fig. 3. Integrated chemical supply chain at different levels of implementation

three months, or *periods*, on which each agent in the system must forecast its own demand, and place orders according to the forecast. The implementation level is represented by the overall performance of the supply chain in a simulation horizon of years. The negotiation process between chain components occurs in the protocol level, and its results affect both the output of the software involved in the contents level and the implementation level.

A distinctive feature of chemicals supply chains is that the plant, which is also called the engineering side of the chain, plays a more dominant role than other chain components. The desired delivery time for the products is often shorter than the production campaign length, and the raw materials supplying time is often long (Janicke, 2000). In addition, the plants are often not flexible and agile enough to be able to respond to the demand of supply chain dynamics. As a result, special attention needs to be paid to the scheduling and control of the plant in addressing chemical supply chain problems.

In this case study, we consider a batch process and its supply chain for manufacturing and supplying paints and coatings. Due to the diversity of end customers, this is an industry that is tightly linked to the state of the economy. The present worldwide demand for paints is estimated at around 22,500,000 tons/year and valued at over £65 billion. The global growth rate will stabilise between 2% and 2.5% per year, and by 2005 demand is expected to exceed 26,000,000 tons, and there will also be a shift in the relative importance of the different geographical regions to North America, Eastern Europe and Asia Pacific (Howard, 1999). Despite the re-structuring of the paint industry usually through acquisition by market leaders, small and medium sized companies still represent no less than 40% of the world market. The ever-increasing competition has forced small and medium-sized companies to become more flexible, and modernise the production lines and distribution networks.

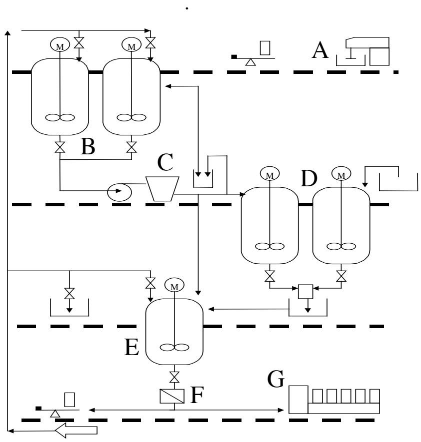

Fig. 4. The batch paint production process. (A – dispersers, B – dissolvers, C – rotary mill, D – paste mixers, E – adjusters, F – Filter, G – packing machine)

Paints and coatings production is performed on *multi-purpose* batch plants, where products can follow different routes through the plant and two or more products may be produced at any one time. Multi-purpose plants are more flexible than *multi-product* plants where all products are produced following the same route, one at a time, the plant is designed for a fixed set of products, and campaigns are carried out for each product in turn.

One of our objectives in developing the system is that it can be used to study the impact of supply chain dynamics on plant operation and scheduling. With this consideration in mind, we assume that the only non-significant delay between agent replenishments occurs when the plant delivers to the warehouses. This delay is equal to the time it takes to the plant to finish the production campaign. At this stage of implementation, no delays are assumed to happen in our model for other agent interfaces.

A generic description of the paint and coating production process can be found in Stoye and Freitag (1998) and Figure 4 shows a simplified flow diagram. This is a typical multi-purpose batch plant where the production stages are arranged vertically. In the upper level, raw materials are weighed and charged into the dispersers (the equipment denoted as A on the flowsheet). These concentrated mixtures pass then to the dissolvers (B) to produce a more diluted mixture. This resin is then pumped and dispersed using an agitator mill (C). After this it goes to the paste mixers (D), where additives including pigments, stabilisers, accelerators, plasticizers and extenders are added. The product goes then to an adjuster (E), where the fine properties required for each specific batch are tuned-up. The paint is finally filtered to remove the impurities and packaged using the packaging machine G.

To describe the production procedure, a state task network (STN) is used. The STN is a directed graph that describes the sequence of activities, represented by rectangles and the states represented by circles that have to undergo in order to get the desired products (Kondili et al., 1993; Papageorgiou and Pantelides, 1996).

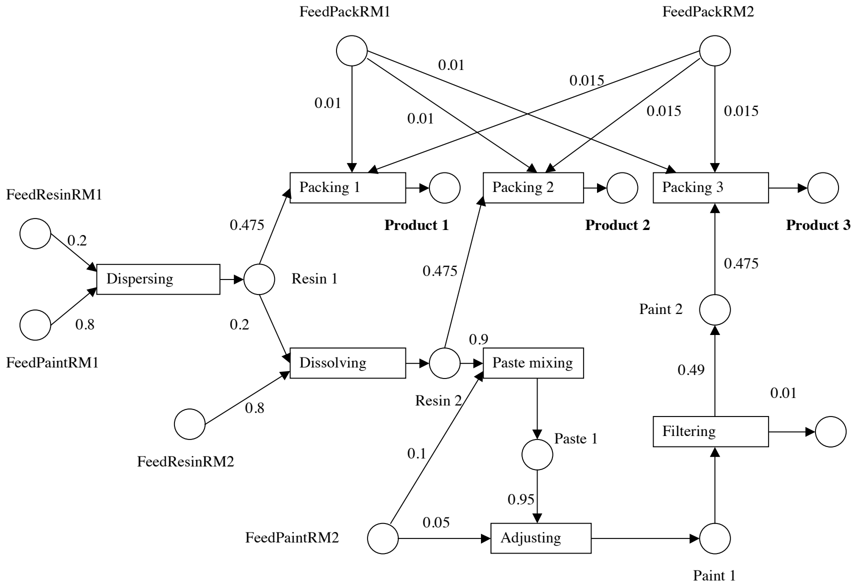

Fig. 5. State task network for paint production process

The numbers attached to the arrows indicate the composition (i.e., the fraction of each state) that enters the following activity. The STN network for the paints and coatings production is shown in Figure 5.

The recipe depicted in this Figure shows that there are three products produced at different stages that can be sold after being packaged. These products are obtained from six different raw materials, each belonging to any of three groups (resin, paint and pack) and named accordingly FeedResinRM1, FeedResinRM2, FeedPaintRM1, FeedPaintRM2, FeedPackRM1 and FeedPackRM2.

The STN network describes only the recipe for production, but does not give information on the equipment used. Different vessels may be used for the same task, or a piece of equipment can be employed to perform more than one processing activity. In addition, there are also storage vessels for intermediate products and finished products. All the equipment considered in the example is listed in Table 2.

The scheduling problem that the plant agent solves is a common operational research problem that may be stated as follows. Given the mode of operation, the product orders, the product recipes, the number and capacities of the various types of existing equipment and the list of equipment types allowed for assignment to each task, determine the order in which tasks use equipment and resources, and the detailed timing of the execution of all tasks so as to minimise the delay in fulfilling orders. To perform this calculation, the commercial package gBSS® optimisation software for multipurpose plants developed at Process Systems Enterprise Ltd. from Imperial College, London, was used to calculate the plant optimal schedule. The details of the mathematical problem formulation can be found in Kondili et al. (1993) and Shah et al. (1993) and therefore will not be described here. However, the

Table 2. Equipment used for production in the case study

Equipment	Unit No.	Capacity (ton)	Function
B100	1	10	Dispersing 1
B110	2	10	Dispersing 1
D200	3	40	Dissolving 1, Paste mixing 1
D210	4	40	Dissolving 1, Paste mixing 1
P300	5	60	Dissolving 1, Paste mixing 1
P310	6	60	Dissolving 1, Paste mixing 1
A400	7	100	Adjusting 1
A410	8	100	Adjusting 1
F500	9	Continuous	Filtering 1
PK600	10	Continuous	Packaging 1, Packaging 2, Packaging 3

terms of the objective function for minimising production make-span are outlined and the values of the parameters used in optimisation are given.

For this problem, the objective function to be minimised is as follows:

F = *Contribution from each order* + *Cost of feedstocks* - *Cost of storage* - *Costs of utilities and tasks* + *penalties*

When the objective is the minimisation of delay in fulfilling orders, a *nominal* and a *hard* deadline must be specified for each order. Any order delivered after the nominal deadline incurs a penalty, which increases with the difference between the actual delivery time and the nominal deadline. If the solution results in all orders being fulfilled by their nominal deadlines, no delay penalty will be incurred. In any case, all orders must be fulfilled by the hard deadline.

When more than one product needs to be produced in a single run, it may be the case that delays in the production of some items are tolerated more than delays in others, so it becomes necessary to assign priorities. When used to minimise delays, gBSS attempts to minimise the total weighed delay in fulfilling orders, where the delay of each order is weighed by its priority. A priority is defined together with the form of the penalty function, which may be linear or square. A very high priority will insure that no delay is incurred unless it is absolutely unavoidable. Orders' priorities must be specified, together with a penalty form F_p. The penalty added to the objective function F is:

IF actual delivery time $\leq$ nominal deadline
  THEN penalty = 0
IF nominal deadline $<$ actual delivery time $\leq$ hard deadline
  THEN penalty = amount delayed * priority * F_p (actual delivery time – nominal deadline)

The penalty form chosen for the simulation (see Sect. 5) is linear and the priority set for all orders is 300. Nominal and hard deadlines were specified as 48 hrs and 144 hrs respectively.

The following assumptions are made for the formulation of the mathematical optimisation model:

(1) The time variable is discretised and the minimum period is 1 hour.

(2) No cleaning operations are performed after each job.

(3) A list of identical units within a stage, as can be found in table 2.

(4) Batch sizes are variable.

(5) There is unlimited storage capacity for intermediates.

(6) The minimal campaign length is set to 48 hours due the shape of the objective function, as has been explained.

In addition, it is assumed that the plant agent performs its inventory management activities in a similar way as the warehouses and retailers do.

5 Simulation considerations

5.1 The inventory policies

Four inventory policies have been implemented, including the *order-point and order-quantity* (s, Q) *system*, *order-point and order-up-to-level* (s,S) *system*, *periodic review and order-up-to-level* (R, S) *system*, as well as (R, s, S) *system* (Silver et al., 1998). The *order-point, order-quantity* (s, Q) *system* is a continuous review system where a fixed quantity Q is ordered whenever the inventory position (i.e., items on hand plus items on order) drops to the reorder point s or lower. The *order-point, order-up-to-level* (s,S) *system*, a continuous review system where an order is placed when the inventory position drops below s, but the amount ordered is variable and is enough as to raise the inventory position to the order-up-to-level S. The *periodic review, order-up-to-level* (R, S) *system* is also known as replenishment cycle system. Every R units of time, enough is ordered to raise the inventory position to level S. Because it is periodic, it offers advantages when coordinated inventory management of related items is necessary. The (R, s, S) *system* is a combination of the (s,S) and (R,S) systems. When using it, the inventory position must be checked every R time units. If it is below the minimum s, an order is placed so to reach the maximum S, but if it is above s, nothing is done until the decision has to be repeated in the next review period.

5.2 Retailers

The retailer agent fulfils the customers' demands on wood paints and coatings. Retailers use a "customer" function that sets boundary marks in demand by defining a monthly rate of demand that the retailers know up to the present moment and whose value they have to forecast for the next period. Retailers strive to fulfil the demand defined by the "customer" function, although their success depends on the warehouses' ability to supply and the success of the negotiation procedure when stock is scarce. The demand forecast is currently made using a weighed averages method. The reason is that this method can easily be adjusted to change the relative importance of the demand in previous months to forecast future demand. Operations research forecasting methods like moving averages or exponential smoothing may be implemented easily at a later stage. With this forecast and the inventory model, the orders are placed to the company (Logistics). Each retailer shares a fraction of the monthly demand through a weight constant.

5.3 Logistics

Logistics receives orders from all the retailers. These will be used together with other information about the physical locations of retailers and warehouses and the transportation cost per unit of finished product per unit of distance. Thus, logistics solves a classical transportation problem where the warehouses have equal capacity to fulfil the retailer's orders.

5.4 Warehouses

Warehouses are distribution centres for the finished products. They place orders to the plant according to their inventory policies.

5.5 Purchasing

The purchasing agent is in charge of ordering raw materials according to the information supplied by the plant.

5.6 Raw material suppliers (RMSs)

Each RMS provides a family of raw materials including resin, paint and package materials. These agents state a price based on the function that the raw material producers provide, and pass it to the company (purchasing agent).

6 Agent communication

The communication action between agents can be explained as follows. After the agent initialisation, an external agent sends a signal to the purchasing agent so to place an order to the raw material suppliers (beginning of period n). This in turn delivers the required raw materials to the plant and simultaneously place an *advertise* performative with the prices (i.e., the prices at period n+1) of the raw materials to purchasing. In turn, the plant *forwards* to the warehouses the materials that they ordered in period n-1 so they can deliver to the retailers according to the optimal transportation plan calculated by logistics in period n-1 for deliveries in the current period, and purchasing forwards to logistics so it can advertise prices for period $n+1$ to the retailers. The retailers then calculate their expected requirements using their inventory levels and forecasting methods and place their *orders* to logistics.

Logistics calculates the optimum transportation schedules for period n+1 given the transportation costs per distance unit, retailers and warehouses locations and supply abilities of each warehouse and proposes this to the warehouses. If the warehouses accept, they place in turn their *orders* to the plant. In contrast, if they reject Logistics' proposal, the negotiation process continues as described in the next Section. In any case, the negotiation process ends when the warehouses place their orders to the plant. Once the Plant receives the Warehouses' orders, it "produces" the materials that will be delivered at period n+1 by running the wrapped optimisation software gBSS, which calculates as a mixed-integer nonlinear program the production schedule that minimises production make-span. Once this has been done, the plant *tells* the warehouses that finished product has been delivered and places its own raw material requirements to purchasing, always according to its inventory levels. These raw materials will be received by the plant at n+1. Purchasing orders again to the raw materials suppliers and the cycle starts again.

As already mentioned, a neutral format for the message contents is necessary. We used the EXPRESS language and XML. One criticism of STEP is that STEP focuses more on data storage, for example, most tools developed are for transfer data between database systems, but less on exchange, particularly over the Internet. XML is now regarded as a potentially more powerful tool for data exchange.

The system starts with the Purchasing agent sending an *order* to the raw material suppliers. If the warehousing policy for the plant is continuous review with S = 1000, s = 500 for FeedResinRM1 and 4000, 2000 for FeedResinRM2, so that inventory is filled up to S in each case. If the plant's stock of FeedResinRM1 runs low at 10 months and FeedResinRM2 runs low at 11 months, the *order* is placed to the raw material supplier 1 (RMS1) with the following performative,

```
(order
   :sender Purchasing
   :receiver RMS1
   :language KQML
   :content ((K 3)(amountsOrdered00(508.49))
             (dueTimes00(10.0))
            (fullPrice00(50849.00))(amountsOrdered01
                                    (2000.46))
            (dueTimes01 (11.0))(fullPrice01(200046.00))))
```

The first piece of information in the body of the message, (K 3), means that the order is being sent in the third round of message exchanges, that is, the third period or planning horizon. The remaining contents are self-explanatory. There are equivalent orders to other RMSs.

A RMS fulfils the order with a delivery of material to the plant (i.e., the RMS communicates about the delivery with a *tell* performative), and at the same time sends an *advertise* to the Purchasing agent of the plant, containing the prices of raw materials for the next period. The buying cost for the raw material supplier are 100 £/ton of raw material, but as there is a gain of 0.2 for the supplier and a transportation cost from the RMS at Hull to the plant at Derby to be considered (0.5 £/ton Km), the price raises (100(1.2) + 0.5(139.8) = £ 189.9). The performatives sent are as follows,

```
(advertise
   :sender RMS1
   :receiver Purchasing
   :language KQML
   :content ((K 4)(unitPrice00 189.91)
             (unitPrice01 189.91)))
(tell
   :sender RMS1
   :receiver Plant
   :language KQML
   :content ((K 4)(amountDelivered00(508.49))
             (deliveryTimes00(10.0))
             (amountDelivered01 (2000.46))
             (deliveryTimes01 (11.0))))
```

Purchasing simply *forward*s the prices to Logistics, as the latter is the responsible agent for managing budget. The plant then sends an empty *forward* to the warehouses to inform them that they can deliver the material requested by the retailers.

Logistics *advertise*s to the retailers the unit prices of its products for this period, considering gain, transportation costs from plant to warehouses and from warehouses to retailers, production costs and number of retailers in an analogous way as RMS did with purchasing, using the following performatives,

```
(advertise
   :sender Logistics
   :receiver Retailer0
   :language KQML
   :content ((K 4)(unitPrice00 162.39)
             (unitPrice01 162.39)
             (unitPrice02 162.39)))
```

Each warehouse delivers (i.e. *tell*s about the deliveries) to the retailers just as the RMS did with the plant. The amounts ordered depend on each retailer warehousing policy parameters. We have one message like this for each warehouse for each retailer.

```
(tell
   :sender Warehouse0
   :receiver Retailer0
   :language KQML
   :content ((K 4)(amountDelivered00
             (112.50 112.50))
             (deliveryTimes00 (10.25 11.75))
             (amountDelivered01 (112.50 112.50))
```

```
                (deliveryTimes01 (10.25 11.75))
                (amountDelivered02 (103.12))
                (deliveryTimes02 (10.75))))
```

The retailers *order* to Logistics. The total monthly demand is 300 ton/month of products 1 and 2, and 150 ton/month of product 3. As there are eight retailers, the monthly demand of each is 37.5 ton/month. The warehousing policy parameters are $S = 300$, $s = 200$, so the order placed is of around 100 ton on each order. The amount ordered comes from what the retailer forecast the monthly consumption of the customers for the next period (a customer is simply the function that defines what the monthly rate of demand is going to be) through a weighed averages method. Following is one of these messages sent by each retailer to Logistics.

```
(order
   :sender Retailer0
   :receiver Logistics
   :language KQML
   :content ((K 4)(amountOrdered00 (112.50 112.50))
             (dueTimes00 (13.25 14.75))
             (fullPrice00 (18269.32 18269.32))
             (amountOrdered01 (112.50 112.50))
             (dueTimes01 (13.25 14.75))
             (fullPrice01 (18269.32 18269.32))
             (amountOrdered02 (103.12))
             (dueTimes02 (13.5))
             (fullPrice02 (16746.88))))
```

With this information, logistics sends the orders of each retailer of each product to the warehouses and solves the transportation problem as explained.

The warehouses *order* to the plant independently, but if several orders arrive at the plant at the same time, it will result in a longer delay in production. This is a sample *order* message,

```
(order
   :sender Warehouse0
   :receiver Plant
   :language KQML
   :content ((K 4)(orderP00
             ((337.50 337.50 337.50)
             (12.75 13.25 14.5)))
             (orderP01 ((337.50 337.50 337.50)
             (12.75 13.25 14.5)))
             (orderP02 ((309.37)(12.75)))))
```

After gBSS finds a minimum make-span schedule, the plant sends the finished product to the warehouses and informs about the delivery through a *tell*, assuming that the delay between order placement and order reception equals the production delay.

```
(tell
   :sender Plant
   :receiver Warehouse1
   :language KQML
   :content ((K 4)(deliveryP10
             ((337.5 337.50 337.50)
             (12.25 13.75 15.0)))
             (deliveryP11 ((337.5 337.5 337.50)
             (12.25 13.75 15.0)))
             (deliveryP12 ((360.93)(14.5)))))
```

The warehouses *report* their performance to Logistics. Afterwards, Logistics pays to purchasing the plant operation costs, transportation costs and raw material price for the next period. Purchasing sends its part of the budget to the plant. The plant will inform Purchasing the raw materials needed for production in the next period. On receiving the message from the plant, Purchasing informs (*report*s) logistics that is ready to purchase raw materials for the next period. Logistics *authorises* purchasing to proceed to buy material for the plant. Purchasing places orders to the raw material suppliers and the cycle of performatives is repeated until the time reaches the pre-set number of periods for simulation.

7 Conflict resolution through negotiation

Three stages are involved in the agent negotiation process for conflict resolution: *proposal*, *counterproposal* and *termination*. A proposal is a solution to a problem proposed by an agent, based on its own knowledge and interests. A counter-proposal is the action taken by the receiving agent of amending the original proposal and sending it back to the originating agent. Proposals and counterproposals can be carried out for a number of times until they reach the state of termination, i.e. the end of a negotiation process. The state of termination may mean that a compromise decision has been reached, or that the negotiation failed. When a number of agents are involved, a co-ordinator is needed which observes the process and makes strategic decisions.

A negotiation process can be conveniently represented by a state transition diagram (Fig. 6). A transition diagram is a collection of circles (states) connected through labelled arcs (transitions). These labels give information about the required input to produce a change of state and/or output. One of the circles has a pointer (the *initial state*) and at least one of the states is represented as a double circle to represent a stop (an *accept state*). In our application, the circles in the transition diagram represent states of an agent when it receives different sequences of performatives from other agents or the environment. The possible sequences are represented as arcs.

The transition diagram in Figure 6 represents a negotiation protocol where the logistics agent acts as a co-ordinating agent involved in conflict resolution with two warehouses. The purpose of negotiation is to reach an agreement on whether the

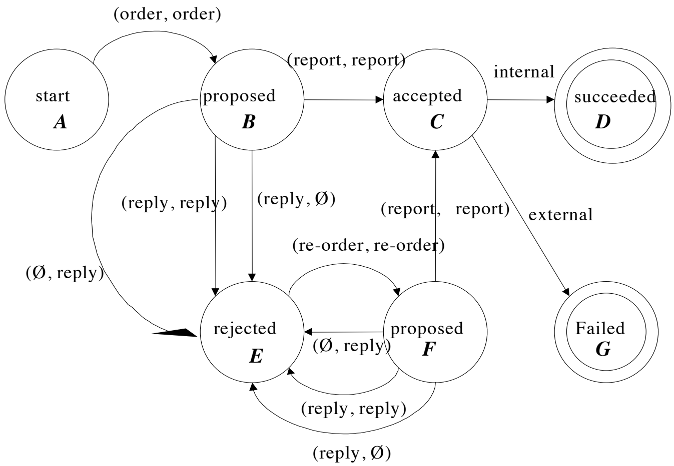

Fig. 6. Transition diagram for anegotiation protocols

warehouses are able to fulfil the Retailers' demand as requested by Logistics. As explained in Section 6, the warehouses have to cope at period n with deliveries that fulfil retailers' demands made in the previous period before receiving their own replenishment for the current period. So it may happen that a large order is received by a warehouse after the reorder point has been reached (assuming a continuous review (s, S) policy). The warehouse knows in this case that its own inventory level is too low, so it can inform logistics that it is not able to deliver as this agent had first requested according to the original optimal transportation schedule. This message is interpreted by the logistics agent as a request for a different solution, and therefore it is a petition to set a different constraint in the transportation problem. The affected constraint is the relative capacity of each warehouse to fulfil orders, set originally to equal capacities. Logistics assigns 1% less capacity to the "grumbling" warehouse until an agreement is reached. If this solution allows acceptable lowest inventory levels during the current planning horizon for both warehouses (that is, until replenishment arrives), the negotiation succeeds. The negotiation process continues until it succeeds or until there is no way to fulfil the demand without incoming shortage, in which case the negotiation fails.

The first word of the pair in brackets that labels a transition in Figure 6 represents the performative sent by the first warehouse and the second label represents the answer of the second warehouse to logistics. The symbol $\emptyset$ represents no answer. The labels internal and external represent the way demand is fulfilled. If negotiation concludes successfully, (node **D**) the supply chain does not require outsourcing. Otherwise external supply is necessary. The negotiation process starts with the logistics agent sending orders to warehouses 0 and 1 (node **A** to **B**). If the orders are accepted by both warehouses, they carry on with their duties, prepare reports and the negotiation is terminated successfully (node **B** to **C** to **D**). If the orders are rejected by at least one of the warehouses (**B** to **E**), the negotiation starts (**E** to **F**). If the inventory level in any warehouse drops below its specified reorder point, it will inform the logistics. Logistics will calculate a new solution with a modified constraint and will send a new proposal. The negotiation will continue until reaching a state of termination (**C** to either **D** or **G**), with a success or failure negotiation result.

The conflict resolution mechanism does not guarantee an optimum solution be found each time, a dynamic simulation can help to evaluate the impact of a compromise decision on the dynamic behaviour of the supply chain.

8 llustrative results of distributed simulation

Simulation of supply chain dynamic behaviour is particularly useful when a compromise decision reached through negotiation needs to be evaluated. The simulation can also be used to study the impact of chain dynamics and uncertainty in demand and supply on the operating and control policies of chain components, such as inventory control policies as well as plant scheduling strategies. In contrast to traditional methods of modelling the whole supply chain as a group of algebraic and differential equations, the current system simulates the supply chain behaviour as a network of distributed and interacting agents, where each can be developed and maintained independently and has its own operations. In this section we present some illustrative results of simulation runs.

8.1 Comparison of different warehouse inventory policies

In this section, we compare results when using continuous review (s, S) and periodic review (R, s, S) inventory policies. The reviewing period is set to one month. The purpose is to demonstrate that various management and control strategies can be evaluated using the distributed simulation system. The customer's rate of demand is considered to be constant at 200 ton/month for products 1 and 2 and 100 ton/month for product 3.

It was found that under continuous review policy there are more withdrawals between orders than in periodic review. This is because the retailers in the previous link of the chain are also able to reorder every month only. Undershoots are also larger when working under periodic review. These differences also have an impact on the production pattern of the plant. Figure 7 shows the production patterns of the plant operating under periodic review with periods of one and two months respectively. Clearly under continuous review policy the plant needs to schedule the production more frequently but the amount of product processed is less in each run. The frequency that a process unit is used increases from continuous review of one month to periodic review periodic review of two months, but the differences in used capacity are not so big.

Of course, reducing the revision period when using periodic review increases the retailers' and warehouses' ordering frequencies and also the intervals between orders in the plant. The periodic review policy is reduced to continuous review when the revision period approaches zero.

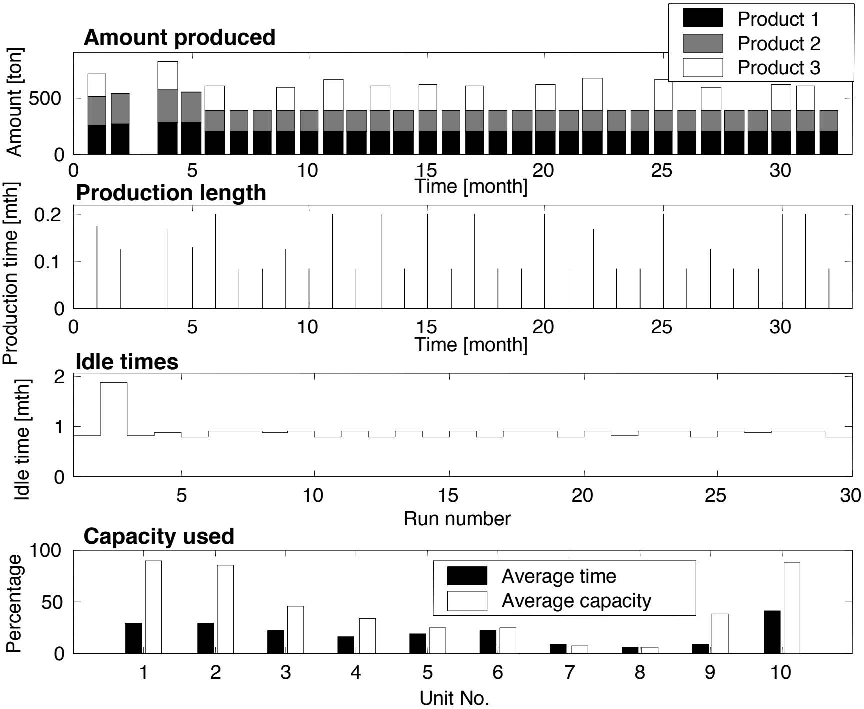

Fig. 7. Production pattern under periodic policy (period = 1 month)

8.2 *Effect of negotiation*

Optimal inventory parameters should minimise the probability of stock-out while keeping the stored amount to a minimum. As explained earlier, when a stock-out happens in a warehouse, the negotiation process is triggered. The results presented here were produced by combining a low reorder point (s is set to 70 tons) with a sudden increase in demand from 200 to 300 tons/month for products 1 and 2 and from 100 to 150 for product 3.

Figures 8 and 9 show the warehouses' inventory levels and the plant production regime when negotiation takes place. The net effect is a hectic delivery schedule for warehouse 0 between months 18 and 21, that is when the increased demand reaches the company's echelon (that is, the warehouses and the plant). No stock-out is incurred by warehouse one due to the negotiation carried out. The effects were also observed for the plant which was under great pressure to satisfy demand for all products between months 18 and 19. There were also longer production lead times that were calculated to optimality and increased transportation cost (Fig. 10). In a first instance, the transportation costs for the "shock period" are considerably larger than at any other time. These costs in following periods are larger than in the time before the increase; negotiation is still necessary after the step increase in demand. A re-tuning of warehousing policy parameters becomes necessary at

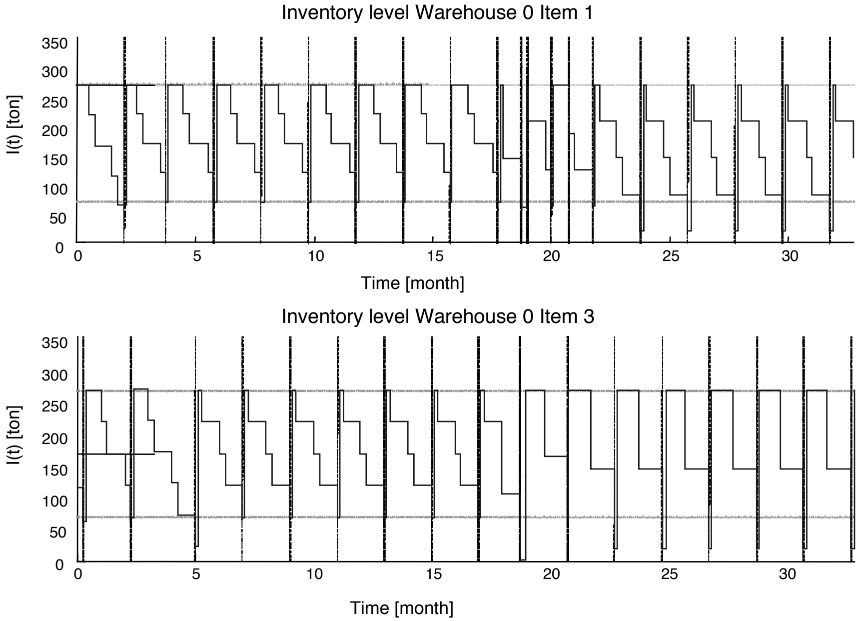

Fig. 8. Inventory plots for warehouse 0 (above) and warehouse 1 (below) when negotiation occurs (reorder point = 70 tons, step increase fromm 200 to 300 tons/month)

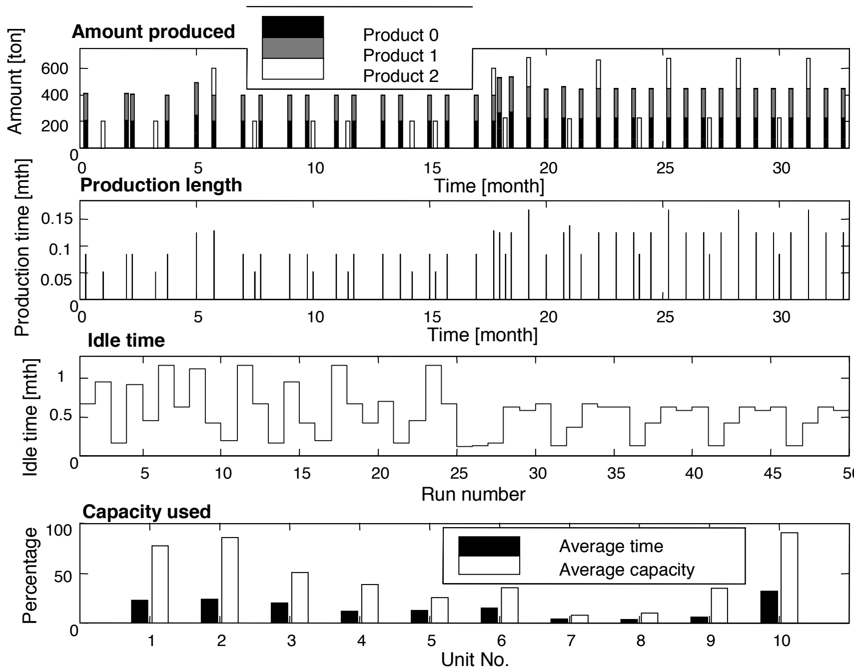

Fig. 9. Plant utilisation record for step from 200 to 300 tons/month (oproducts 0 and 1) and 100-150 tons/month (product 2) using negotiations, r= 70 tons

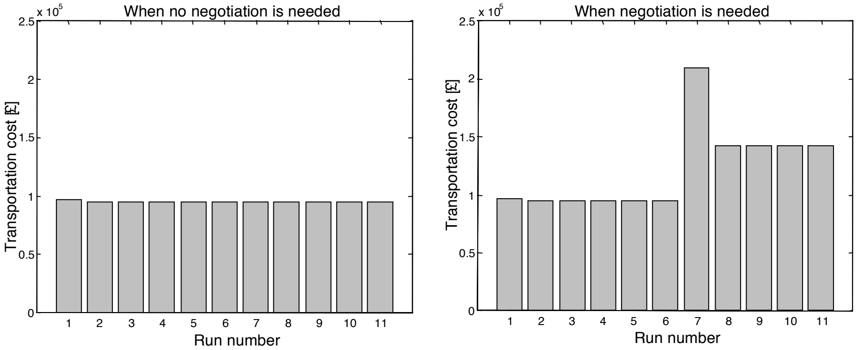

Fig. 10. Transportation costs with no step (left) and when negotiation takes place, step 200-300 tons/month for product 1 and reorder point set to 70 tons (right)

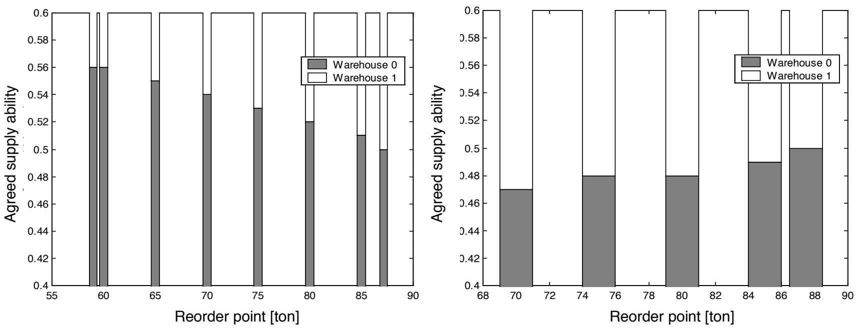

Fig. 11. Agreed supply abilities of each warehouse as a result of negotiation with a step of 200–250 tons/month (*left*); 200–300 tons (*right*)

this point to avoid all the inconveniences caused by plant overload, stock-outs and increased transportation costs.

Figure 11 shows the final agreed supply amount for each warehouse after negotiation has succeeded when the minimum inventory level s (identical in both warehouses) is set to different values. When the value of s exceeds a certain value, no negotiation is necessary and the initial constraint of equal warehouses' ability to supply is enough to satisfy demand; when the value of s is too small, there is no agreement possible and at least one of the warehouses necessarily incurs in stock-out. Figure 11 shows that the range of s for which negotiation can take place is wider for a small increase in demand. It can also be seen that the last cession of supply ability before negotiations fail is larger for the small increase ($|0.5\text{-}0.56|$) than for the large increase ($|0.5\text{-}0.47|$), so it can be said that small increases in demand allow the system to show more flexibility than large perturbations.

9 Concluding remarks

The architectural and functional characteristics of a multi-agent system for chemicals supply chain simulation and management support has been described. The agent-based architecture provides a natural paradigm for implementing distributed and co-operative systems over the Internet. Geographically distributed supply chain components including retailers, warehouses, chemical plants, logistics and raw material suppliers are modelled as a network of agents, each with its internal models and algorithms and being able to communicate with others. This is a flexible and open structure because it can be easily maintained and reconfigured when chain structure is reorganised.

It has also been shown that supply chain behaviour can be analysed using the distributed simulation system. The results have shown a sensible behaviour of the plant production patterns. The system has also demonstrated the potential to be used to study how to improve the plant production scheduling and control policies in order to cope with the uncertainty of chain dynamics. Using the prototype, it has been shown that re-tuning of warehousing policy parameters became necessary after a steep increase on demand in order to avoid inconveniences produced by plant overload, stock-outs and increased transportation costs. However, a specific feature of agent systems (automated negotiation) managed to avoid stock-outs and keep service level standards at the most difficult moment combining varied OR techniques.

Study on supply chain dynamics may also have an impact on the way a manufacturing plant is designed. Traditionally the plants are not designed flexible and agile enough to respond to changes in the market environment. Plants that are part of an ever-changing economic environment should be designed to be re-configurable within hours rather than days and even weeks in order to satisfy ever-changing demand.

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