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An advanced agent-based order planning system for dynamic networked enterprises

AMÉRICO L. AZEVEDO, CÉSAR TOSCANO, JORGE P. SOUSA and ANTÓNIO L. SOARES

Keywords Networked enterprises, Supply-chain management, Multi-agent systems, Decision support systems, Production planning and control

Abstract. There is an increasing interest in exploring the opportunities for competitive advantage that arise from reinforcing core competencies and innovative capabilities of the individual companies, and by forming integrated supply networks. In complex and dynamic environments such as the automotive and semiconductor industries, managing and co-ordinating the procurement of materials, their transformation into intermediate and finished products, and the distribution to the final customers, are very demanding tasks in terms of information systems. In general, current available software packages do not provide the full support needed for networked and distributed organizations, and are clearly insufficient in what concerns the planning and coordination activities needed in these heterogeneous environments. In order to adequately tackle these problems, this work proposes a *multi-agent system* architecture for real-time customer-order planning in distributed manufacturing enterprises, addressing the requirements of a *make-to-order* environment.

The present research work resulted from the Co-OPERATE

Authors: Américo L. Azevedo, Jorge P. Sousa and António L. Soares, Faculdade de Engenharia da Universidade do Porto and INESC Porto, Rua Roberto Frias 378, 4200-465 Porto, Portugal and César Augusto Matos Toscano, INESC Porto - Rua Roberto Frias 378, 4200-465 Porto, Portugal. E-mails: {aazevedo, ctoscano, jsousa, asoares}@inescporto.pt

AMÉRICO L. AZEVEDO has a PhD in the area of advanced planning systems for networking enterprises. Since 1988, he has been teaching Electrical and Computer Engineering at the School of Engineering in the University of Porto, and since 1995 he has been Researcher and Project leader in INESC Porto. His main research interests are in the Virtual Enterprises and Organizations, Integrated Manufacturing area, Industrial Organization and in Production Planning and Operations Management.

CÉSAR TOSCANO has a degree in Electrical Engineering from the Engineering Faculty, University of Porto (1985). Currently, he is Senior Technician in the Manufacturing Systems Engineering Unit of INESC Porto. Among previous positions, he was Scientific Associate in CERN, Conseil Européen pour la Recherche Nucléaire (1988). He participated in several R&D European projects: B-MAN, Business Mobile Agent Network, MyFashion.eu, Co-OPERATE, and X-CITTIC. He has interests in Information Systems Development, Systems Architecture, Distributed Systems, Enterprise Integration, Enterprise Modelling and Supply-chain Management.

JORGE P. SOUSA has a PhD in Operational Research from the Université Catholique de Louvain, Belgium (1989). He is Associate Professor at the Faculty of Engineering, University of Porto and Researcher at INESC Porto, leader of the area on 'Collaborative Business'. He has participated in European projects such as X-CITTIC, CO-OPERATE, EXPIDE, THINKcreative and COMPANION and has published papers in several international journals. Main areas of research: Decision Support Systems, Combinatorial Optimization, Operations Management, Enterprise Networks and Virtual Organizations.

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ANTÓNIO L. SOARES has a PhD in Electrical and Computer Engineering (1998). He is an Assistant Professor at the Faculty of Engineering of the University of Porto and researcher at INESC Porto. His research work has been in the areas of socio-technical design of information systems, requirements engineering and information systems for manufacturing applications. His current research interests lie in the analysis and design of socio-technical networks, in the application of social models to the modelling of socio-technical networks and in collaborative business.

European Project. Enhanced visibility of information, early warning of disturbances, synchronized production and collaborative planning in the supply chain are the general goals of the project. In particular, for aggregate planning and order promising, a distributed and decentralized information system, based on an architecture of agents and extensively using the internet, was designed and implemented. This system aims at responding to the basic requirements of cooperativeness, integration and configurability, and at providing new and more powerful decision support.

1. Introduction

New and more demanding requirements in terms of product innovation and market responsiveness have strongly increased the need for agility, and are therefore forcing many companies to improve their organization and structure. Increased agility is often achieved through the establishment of temporary production networks, as an attempt to satisfy both customer expectations and long-term enterprise goals and viability. Agile, market-responsive supply networks must deal with a rather volatile demand, and one possible way to cope with this variability is through frequent network reconfigurations and the implementation of new business processes.

In a given network the needs of each node will vary depending on the primary focus of the collaboration and on the nature of the product or service provided. In a traditional supply chain, each chain member or node is a separate entity that may be highly integrated internally but with rigid business processes when viewed from the outside. Customer orders are passed up the chain through each partner and products then flow back down to the end customer in an opposite sequence.

In order to provide higher levels of agility, we are here looking at temporary organizations that are formed by networks of enterprises structured at different levels. The concept of 'virtual enterprise' responds fairly well to this challenge. It combines features of a fully market-oriented organization, such as legal independence of the entities and specialization of functions, with features of cooperative forms of organization, such as close collaboration involving integration of information and trust among the participants.

In fact, cooperative networks of companies can be made up of many different entities and various types of interaction may take place. The coordination of participants and the access and sharing of knowledge and information are becoming increasingly important. Moreover, setting up the network and managing it in an optimized way, balancing customer needs with increased performance along the whole network, may be a key factor for the competitiveness of a company. In particular, a lot of attention should be given to the design of effective methodologies and tools to support cooperation and collaboration, as applied to processes such as aggregate planning and customer order negotiation.

It is widely recognized that currently available commercial packages such as enterprise resource planning (ERP) and supply chain management (SCM) systems do not fully provide the support needed for managing networked and distributed organizations, in particular concerning planning and coordination activities (Azevedo and Toscano 1999, Pillep *et al.* 1999, Roux *et al.* 1999).

In this paper, we first try to identify some gaps and limitations of some of those systems that claim to support e-Business and e-Work in networked enterprises. The outcome of that analysis has resulted in a set of requirements for information systems that take into account the new ways of working and doing business. We then propose a new approach for the design and development of distributed information systems, addressing the basic requirements of cooperativeness, configurability and efficiency.

The paper is organized as follows. First, the context is given followed by a brief identification of the main gaps and limitations of current management systems concerning business networking and in particular the activities of operations and logistics management. The paper then presents the general approach and solution considered in the scope of the research project Co-OPERATE (Collings and Loeh 2000). An advanced multi-agent system addressing the requirements of a make-to-order business environment and supporting the processes of real-time order negotiation and planning in a dynamic network of enterprises is then described. Finally, some concluding remarks and current directions of research are presented.

2. Requirements

Networked and 'virtual' enterprises are becoming a new organizational paradigm, creating challenging opportunities in terms of management. The coordination and optimization of complex and dynamic supply and production networks, consisting of independent and autonomous companies, require a thorough rethinking of traditional business processes and the definition of new collaboration methodologies (Beamon 1998).

In fact, full benefits of a close cooperation within the production network can only be achieved when the individual companies are able to interoperate at the business processes level. By adopting new approaches for supply-chain integration and collaboration, companies can achieve significant returns through efficiency improvement, higher delivery reliability, better asset and capacity utilization, faster time to market and responsiveness (Lee and Whang 2001). This is particularly important in the complex and highly dynamic environment of the automotive and electronics industries.

In global environments, operations and logistics management activities differ in several key aspects from the case of an isolated and domestic enterprise. The traditional business paradigm does not adequately consider the fact that a company is in general a part of a much broader matrix of business systems composed of customers, suppliers, products and information. Moreover, traditional principles for enterprise management, based on an environment tailored for mass production and stable markets, are no longer sufficient. As a recent general trend, companies are focusing on their core competencies, with a large recourse to subcontracting, leading to very complex links in terms of information systems.

Scheduling production in a large manufacturing environment requires a real-time knowledge of the status of the resources, of the availability of manufacturing lines, of inventories, etc. In general, current systems do not fully provide a real-time flow of information between any given plant and the rest of the supply chain. Rather limited functionality is available concerning integrated planning and optimization of the manufacturing network. In particular, this is the case for processes such as promising a delivery due date to a customer order (available-to-promise activity), providing active early warnings across the whole network, and solving the problems related to large overstocks, long throughput times and reduced responsiveness to unplanned events (Westkamper 1998).

On the other hand, it is recognized that there is a lack of simple and low-cost solutions for small and medium enterprises, capable of increasing their responsiveness and their level of integration into existing networks (Pillep *et al.* 1999). In general terms, information systems supporting dynamic networked enterprises should be able to (Azevedo and Toscano 1999, Azevedo *et al.* 2001):

- promote collaboration among trading partners for intelligent decision-making;
- increase overall visibility, in order to respond to supply-and-demand volatility;
- handle disturbances (re-planning, encompassing repair methods);
- improve overall process throughput and asset utilization;
- work simultaneously with different planning concepts;
- support heterogeneous environments;
- accommodate new markets and customers and allow continuously evolving business models.

This work aims at partially addressing these issues, by proposing an infrastructure capable of integrating the most important global business processes and making them interoperable.

It should be noted that substantial research has been done on topics such as decentralized production management systems (Richards *et al.* 1997), network organizations (Ching *et al.* 1993, Sauer and Bruns 1995), supply-chain management systems (Fox *et al.* 1993, Thomas and Griffin 1996) and decision support systems for order planning (Kingsman *et al.* 1993, Leachman *et al.* 1996). On a parallel direction, a number of international projects addressed different aspects of virtual, extended, distributed, dispersed or networked enterprises. Examples are the following projects supported by the European Commission: X-CITTIC for designing an enterprise-wide production planning for semiconductor enterprises (X-CITTIC 1996) and PRODNET for developing a reference architecture and an open platform to support virtual enterprises, with special focus on small and medium-sized enterprises (Camarinha-Matos *et al.* 1997).

Still more recently, several other projects and initiatives are trying to understand how successful cooperation takes place among companies, and providing tools to support certain aspects of that cooperation. See, for example, the SCOOP project that addresses the problem of managing cooperation in dynamic SME networks using cooperative planning and control (Ryba *et al.* 2001), or the iViP (integrated virtual product creation) initiative that was set up with 51 partners from industry and research to develop high-tech software products to support all phases of the product creation process, with a particular focus on the integration capabilities of the software tools developed (Bubner and Kühnast 2001). Another example is the GNOSIS-VF project that aims at proposing solutions for the management of a virtual factory of networked resources (Gnosis 2001).

3. General approach and solutions

The general approach and solutions presented in this paper have been designed in the Co-OPERATE Project, aiming at developing solutions to enhance the entire supply network, from the OEM manufacturer to the original material supplier. In order to effectively respond to the general requirements stated above, a set of distributed business processes were identified that have been validated by the companies in the project and will hopefully be easily extended to other industries.

These 'business solutions' (associated to the general functionality of the system) have been defined taking into account the network aspects of the processes and trying to accommodate and support the current internal tools and processes of the companies. A brief description of each business solution (process) follows.

(1) *Long-term business planning for the network*. The goal is to generate long-term plans for the network by synchronizing forecasts and plans, and by promoting early communication of changes and feedback about feasibility.
(2) *Standard operational order and planning processes*. This includes order generation and transmission, synchronized planning, monitoring and status information. It should provide a strong basis for real-time order promising and exceptions handling.
(3) *Feasibility studies for new order or change requests across the network*. To support and coordinate feasibility checking at the individual companies in the shortest possible time. This includes checking of capacity and materials from suppliers.
(4) *Exception handling process*. Includes methodologies to early detect problems in the network such as peak orders, capacity shortages or part availability problems.
(5) *Multi-sourcing coordination*. To optimize the allocation of work to the different suppliers, based on a defined set of rules and fast negotiation methodologies with the suppliers. It includes a negotiation process on capacities with feedback from the suppliers.
(6) *Process visibility*. Methodologies to monitor the progress of orders in the supply network.
(7) *Performance management information*. To provide management information about the performance of the network processes. It includes the identification of key performance indicators and tools to collect relevant data for their computation and presentation.

In this work we have concentrated on the third of these processes that basically involves aggregate planning and order promising performed in a distributed way. In contrast to centralized planning systems, a decentralized approach naturally partitions global complex planning problems into smaller specific problems that are tackled by (local) independent organizational units.

Our research has shown that traditional enterprise information systems do not suitably cope with some of these new demanding requirements of a distributed and heterogeneous manufacturing environment. In particular, for order negotiation and planning, we need to have:

- support for decision autonomy and proactiveness, besides basic decision-making functionality;
- new communication paradigms to help the implementation of delegation and coordination;
- new planning methodologies based on negotiation and in cooperation strategies;
- intelligent functionality integrated into management applications.

These issues lead us naturally to explore the benefits of a distributed approach, based on a framework of multiple agents that communicate through 'speech acts' of advanced languages. Multi-agent systems, due to their nature, seem to be well suited to model dynamic networks of enterprises, as they naturally provide a set of features that make the implementation and the operation of complex distributed systems easier (Azevedo and Oliveira 1999). Fundamental notions about multi-agent systems can be found in the work by Sycara (1998), organized around the concept of problem-solving coherence.

In the literature we can find abundant references to agent-based systems, used to tackle complex situations involving, for example, planning and scheduling and other optimization problems (Fischer 1998). However, most of the multi-agent approaches described in the literature are oriented to very specific applications of an operational nature. There are very few applications of agent-based approaches for more tactical and less structured problems, as it is the case of some problems occurring in production management for networks of enterprises.

This work proposes a global approach that includes a collaborative planning methodology, supported by an information system based on several autonomous units: one for each node in the network. These units are able to perform a set of activities and to anticipate the consequences of their actions, within the scope of their commitments. Each unit is modelled as a set of agents, with features of major importance for the effective management of a cooperative and distributed manufacturing environment: autonomy, proactivity, sociability and responsiveness.

A *software agent* is viewed as a system in a given environment that senses that environment and acts on it, over time, in pursuit of its own agenda and so as to affect what it senses in the future (Franklin and Graesser 1996). Other definitions of the concept can be found in Nwana (1996), where a software agent is seen as a component of software and/or hardware, which is capable of acting exactingly in order to accomplish tasks on behalf of its user.

In fact, by having a set of agents communicating and cooperating with each other, we can address richer and more complex problems, and can increase both the functionality and the efficiency of planning processes. Additionally, a natural support is provided for the whole life cycle of the enterprise network, especially in what concerns: its set-up, in a static or in a dynamic way; the propagation of information through the network (e.g. the announcement of a customer order); the negotiation process between units, leading to a global production plan; and the distributed control and 'traceability' of manufacturing orders throughout the chain.

In the Co-OPERATE system each agent in a network node plays one or more roles. Adding or removing an agent results in the reconfiguration of the roles played by a node, making it easy to add or delete roles in each node, with no disturbances in the network (no changes are needed for the other nodes). The basic functionality for effective agent cooperation will be directly implemented in an infrastructure that provides the basic services for that cooperation.

4. A multi-agent-based prototype

4.1. *Basic architectural principles*

We consider a software agent-based system structured around the following basic architectural principles:

- each business unit in the network of companies is served by a set of agents;
- these sets are 'nodes' in a community of agents distributed by the several 'business units' in the network;
- in each node, the agents cooperate to achieve local goals;
- in each node, each agent performs one or more functions, and coordinates its decisions with the other agents in the node;
- in each node, the users playing the role of planner or configurator totally control the scope of the decisions made by the planner and the capacity agents;
- different nodes in the network cooperate to achieve global or local network goals – cooperation between nodes is carried out through the interactions of the individual agents in the different nodes;
- the functionality across the network is achieved through the interaction of the different nodes;
- the types of agents in each node depend on its required functionality.

Some of the agents in a node have external visibility, thus interacting with agents in the other nodes of the network, whilst some agents have a local scope, being limited to accomplishing local goals. Agents belonging to different nodes and carrying out direct conversations between each other, give support to the global network planning procedures.

In order to support the negotiation dialogues between the business units in the network, we have considered some specific *organizational agents*, referred to here as *communication facilitators*, or simply as *facilitators*. These agents provide communication services such as *registering* or *localizing* agents according to their expressions of interest or knowledge, *forwarding* messages, *routeing* messages based on their content, and *providing mediation and translation services*. Facilitators do not directly carry out any operational function in the enterprise network. A two-level hierarchy of facilitator agents mediates and coordinates local interactions (between the agents inside a node) and network interactions (between agents located in different nodes in the network).

The structure of the network is dynamic: nodes may be inserted or deleted from the network during a reconfiguration process. This set-up is accomplished through registration dialogues between each local agent and one or more facilitator agents. *Registration* actions create a network of agents that will then be organized or configured according to the specific features of the network under creation.

4.2. *Structure of a network node*

Each node in the network is organized as a collection of *roles*, standing in certain relationships to one another, and taking part in systematic and institutionalized patterns of interactions with other roles (Wooldridge *et al.* 2000). This definition involved the characterization of:

- interactions with other roles, according to some protocol;
- responsibilities, determining functionality, in a direct or indirect way;
- set of permissions, which identify the 'rights' associated with the role, and subsequently identify the resources that are available to that role when its responsibilities are placed into practice;

Table 1. Types of agents.

Legacy information integrator	• provides an information service • collects and aggregates information supplied from different legacy sources • propagates information to other required agent types
Facilitator	• acts as an organizational agent and is responsible for providing support to other agents, e.g. it provides services to find the location of external agents of a given type or having certain specific skills or properties
Cooperative planner	• cooperates with other planners in other nodes, in order to develop plans that achieve the network goals • interacts with the local *capacity agent*
Capacity agent	• dynamically evaluates the availability of the business unit for order requests • integrates a local *capacity model* with tailored algorithms • interacts with the *cooperative planner* and the *legacy information integrator*
Monitor	• acquires and aggregates the network or supply-chain state variables; compares current state variables with target values • identifies deviations or disruptions, e.g. resource failure (loss of production capacity), logistic problems (transport delays), quality issues • propagates warnings to other agent types

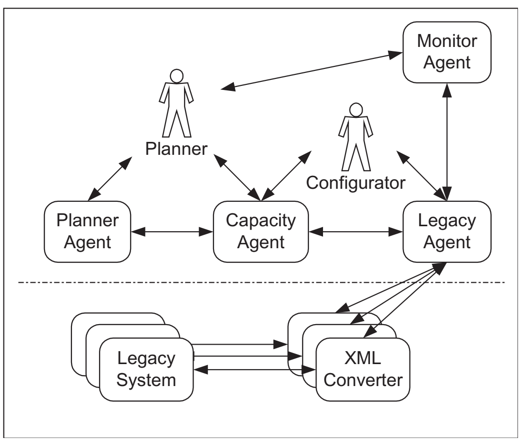

Figure 1. Organization of agents in a network node.

- local computations or activities (i.e. activities with no interactions with other roles).

These features were used to derive the agent types that make up the system, the services required to perform the roles, and the required patterns of communication between the different agent types. Table 1 identifies the agent types needed to support the organization of each node in the network. Basically, an agent type corresponds to a certain combination of roles. This may be a one-to-one correspondence (a very unusual case) or a many-to-one mapping. This is the normal case, where a set of roles is attached to a single entity, this allocation being driven by a number of different types of requirements.

The basic agent architecture for each network node is represented in figure 1. Naturally, these agent types have to be instantiated into agents for each site implementation, requiring the necessary interface with the human agents, namely the *planner* and the *configurator*.

Monitor agents enable conversations between each network node, supporting therefore the propagation of events detected locally. Similarly, the insertion of a new order in the system is accomplished by negotiations carried out between planner agents. Facilitator agents, located in some given sites of the system, support the set-up of conversation and negotiation sessions between the planner and the monitor agents.

Figure 2 identifies schematically the global organization of this multi-agent system. Each business unit in the network is represented by a set of agents that can communicate locally. Negotiation processes between two different business units are accomplished through planner agents. Facilitator agents are not represented in the figure, in order to keep it simple.

4.3. *Integration of legacy systems*

One major concern in designing an information system for a network of heterogeneous companies involves the interfaces for the integration with the various local management systems. Given the intrinsic complexity of such a task, it is not feasible to use traditional ways for designing every specific interface with each particular system.

In line with Co-OPERATE main goals, a generic integration interface infrastructure has been designed. This infrastructure is then deployed on top of the existing systems or infrastructures, to support the network processes of cooperation between companies, in a way that

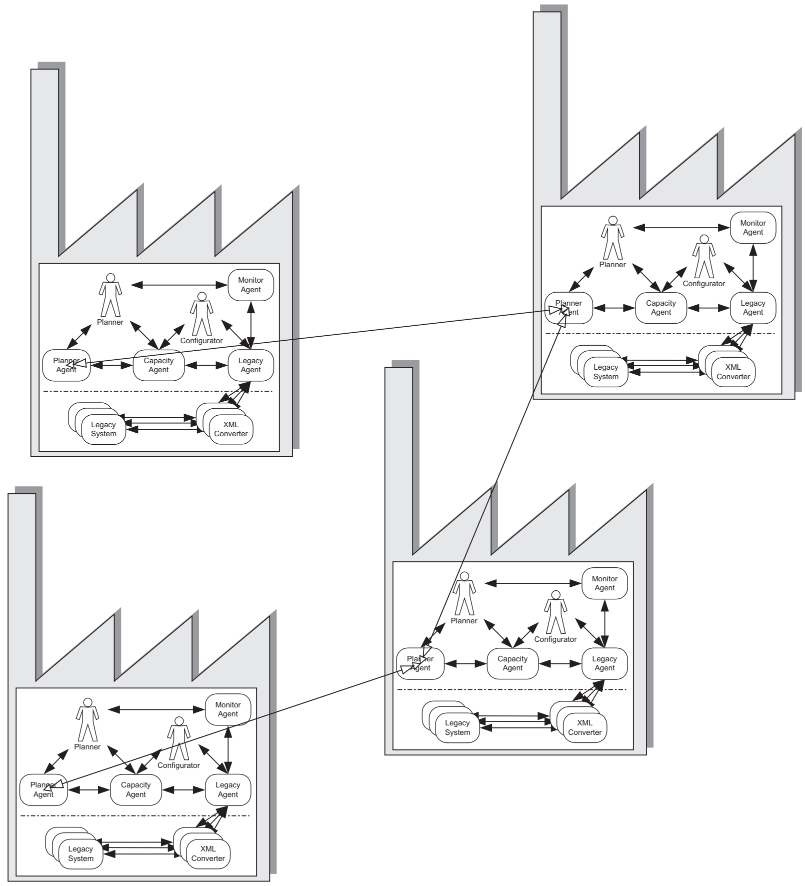

Figure 2. The business network modelled as a multi-agent system.

is complementary and independent from the processes managed by the existing systems.

In order to build meaningful models, data from the legacy systems from each network node have to be imported. For example, aggregate high-level data models, reflecting the actual production availability of a certain unit, must be built by the capacity agent, based on the data managed by the manufacturing execution system, internal to the unit.

In the single-node context, integration with the existing legacy systems is divided into two phases. The first, most basic, phase handles connectivity between the different systems. For each legacy system, a software program is envisaged, with the objective of converting raw data, presented in a specific and usually proprietary format, into a general and standard format. For this purpose XML was chosen, mainly because it is currently recognized as a 'standard' language to describe data in the internet environment, and also because there are some relevant ongoing efforts for developing specific XML applications (RosettaNet, ebXML, Microsoft, BizTalk, etc.). This approach reduces the original integration problem to a more specific problem of converting data coded in different formats into generic and recognizable conceptual data.

The *legacy agent* accomplishes the second phase of the integration. Its purpose is to collect, process and assemble the raw data managed by the legacy systems such as enterprise resource planning (ERP) or manufacturing execution systems (MES), and provide high-level conceptual data, required by the agents to perform their tasks. Normally, the low-level raw data are too detailed to be directly used by the agents in the system. Additionally, data coming from different sources may be insufficient or may lead to inconsistencies in subsequent stages. The main functionality of this layer is the development of appropriate abstractions and aggregations in the low-level data. Further, the legacy agent mechanisms deal with inconsistencies, conflicts and inaccuracy in the data that are provided by the legacy systems. Moreover, the legacy agent provides an interface with a human expert analyst who will validate data and set the values of some configuration parameters.

4.4. *Capacity models*

Local capacity agents are based on specific capacity models that try to capture the singular features of each site, and to provide a mechanism to check capacity each time an enquiry is performed or an order insertion attempted. These software components interact with the ERP system at an upper level, and with the MES system on a lower level. These interactions feed the model with data about time-based resource availability. As mentioned above, the legacy agent, using an XML communication format, provides this interface.

The model is not only a repository of dynamic data, but it is designed around a set of flexible and user-configurable algorithms. These algorithms dictate the way the model behaves, and range from very simple mathematical models to more advanced specific tools, based on cycle time analysis (Leach and Ristic 1998) or bottleneck detection mechanisms (Bastos and Sousa 1998).

Since the production systems under consideration are heterogeneous and can be modelled with different degrees of detail, it is very unlikely that a generic solution can be designed. Therefore, in order to make the structure of the capacity model flexible enough, a dynamic instantiation mechanism of algorithms was implemented. This approach enables the user to design different algorithms, and depending on the particular features of the production system, the user can dynamically instantiate the algorithm that better fits into that specific system. Our goal was therefore to construct a generic and flexible software component that could be used in very different types of industries and in very different units of the supply network. For that purpose, the expert user is asked to configure the system, using his/her experience and know-how in capturing the specific system singularities and in translating them to the capacity model.

The performance of the model can be adequately evaluated by measuring the time required to set up and start running the model (that depends on the volume of legacy data in the unit) and by the time required for the capacity model to respond to requests from the other components, namely the cooperative planner agent. This time is obviously dependent on how detailed the model is. With a very rough capacity model, the responses are fast, but not so accurate or reliable. On the other hand, if the model is more detailed, the responses become much more accurate, but they take a much longer time to be produced.

Several key concepts form the basic (aggregate) elements of the capacity model developed:

- *Meta-product*: group of products (finished products or product families) that have similar characteristics concerning their production processes (here similarity is considered at the level of aggregation dealt by the model).
- *Macro-operation*: aggregation of several sequential operations with similar characteristics. These operations are viewed as one basic macro-operation, with a single capacity. A macro-operation is a high-level conceptual operation that characterizes a set of real production operations.
- *Resource-centre*: aggregation of a set of shopfloor work-centres. It represents the bounding capacity resource for a specific macro-operation.
- *Production-routeing*: the sequential set of macro-operations that have to be carried out in order to manufacture a single meta-product.

To each resource-centre an effective (probably not constant) capacity along the planning horizon is assigned. The following items form the basic data the model requires from the company's ERP system:

- *Product identification*: unique reference of each product (finished product or product family) supplied by the company to its customers.
- *Product bill-of-material*: component parts required for each product; the companies that supply those parts.
- *Forecast demand*: estimated quantity demanded by the customers in each time period of the planning horizon.
- *Backlog*: orders already committed by the customers along the planning horizon; backlog orders partially consume forecast orders.
- *Master production schedule*: quantity to be delivered by the production unit in each time period of the planning horizon.

In its current version, the capacity model does not depend on the particular production environment and on the implementation details. The integration with the capacity agent is obtained by encapsulating the capacity model and its functionality. As a result, we have a generic and flexible capacity agent, able to negotiate order insertions and changes in a multi-agent environment, and a specific capacity model able to model the unit production availability.

4.5. *Negotiation between planner agents*

The interaction between different planner agents is based on negotiation and it is supported by a variation of the *contract-net* protocol. There are two types of entities in a negotiation dialogue: the *initiator*, which starts the conversation process, and the respondents. Figure 3

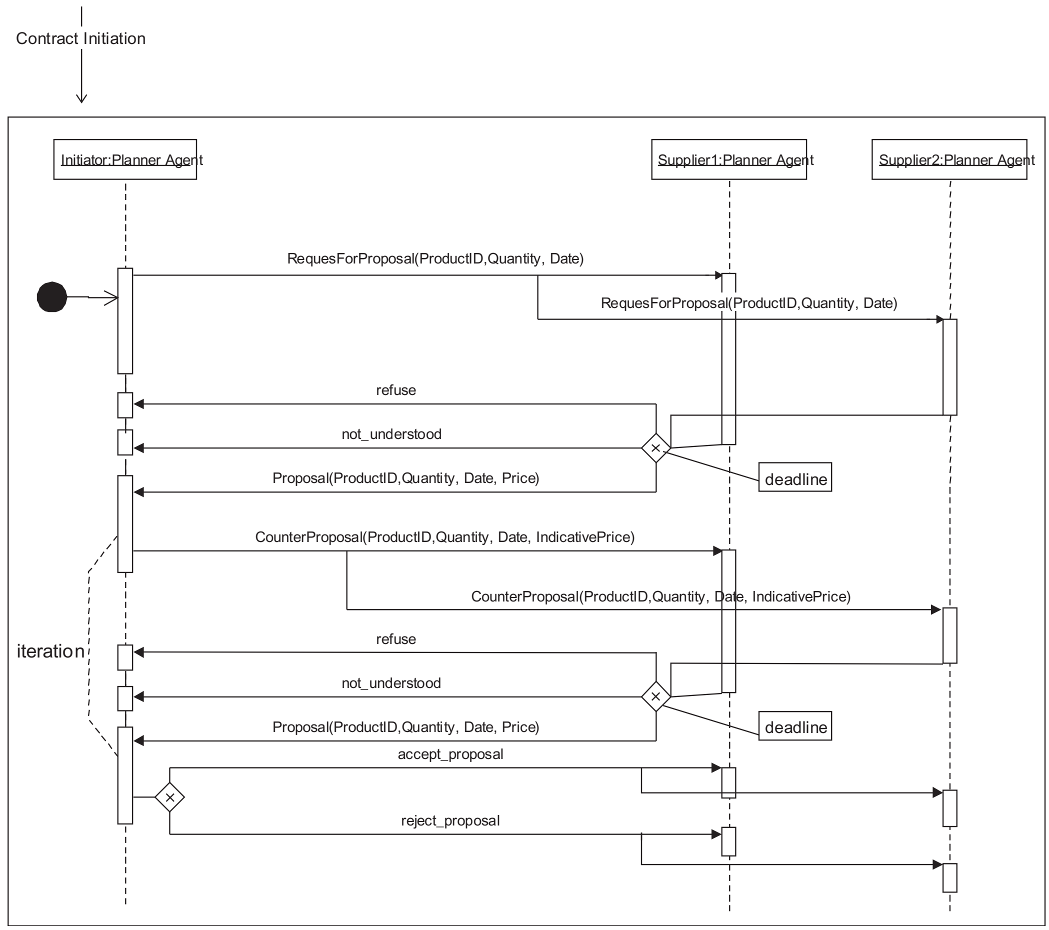

Figure 3. Negotiation process involving three planner agents.

describes a simple scenario, where two planner agents, representing two different business units in the network, have the role of supplying finished goods to another business unit in the network, illustrated by the planner agent at the left of the figure.

A negotiation process is started when the initiator formulates and issues a *request-for-proposal* message to a group of previously selected targets. In the example, these targets are the planner agents representing the supplier units in the network. Each of these entities either *refuses* the request or constructs and sends a proposal to the initiator. This call for proposals and subsequent interaction may be repeated several times. At each stage, each respondent planner agent constructs a response, based on the current unit status and the adopted general planning strategies. The negotiation terminates as soon as the initiator, according to its local strategy, decides to accept one of the proposals analysed in the latest iteration, and to refuse all the others.

Research is currently being conducted in order to enhance the negotiation process, by designing appropriate strategies for the initiator role and for the respondent role.

4.6. *System implementation*

A first prototype of the multi-agent system described in this paper was developed, having been tested and evaluated by the end users of the Co-OPERATE consortium. Figure 4 depicts the actual configuration of the system.

The supply chain is formed by three main nodes of a dynamic supply chain (in the first, second and third tiers of the supply chain), involving different industry domains, namely the automotive and the semiconductor industries. The software agents of each node in the network (business nodes) are all deployed in the same host machine (although they communicate with each other as if they were deployed in different computers in a network of computers).

The planner of each enterprise accesses the software agents through an internet browser. A JAVA applet is

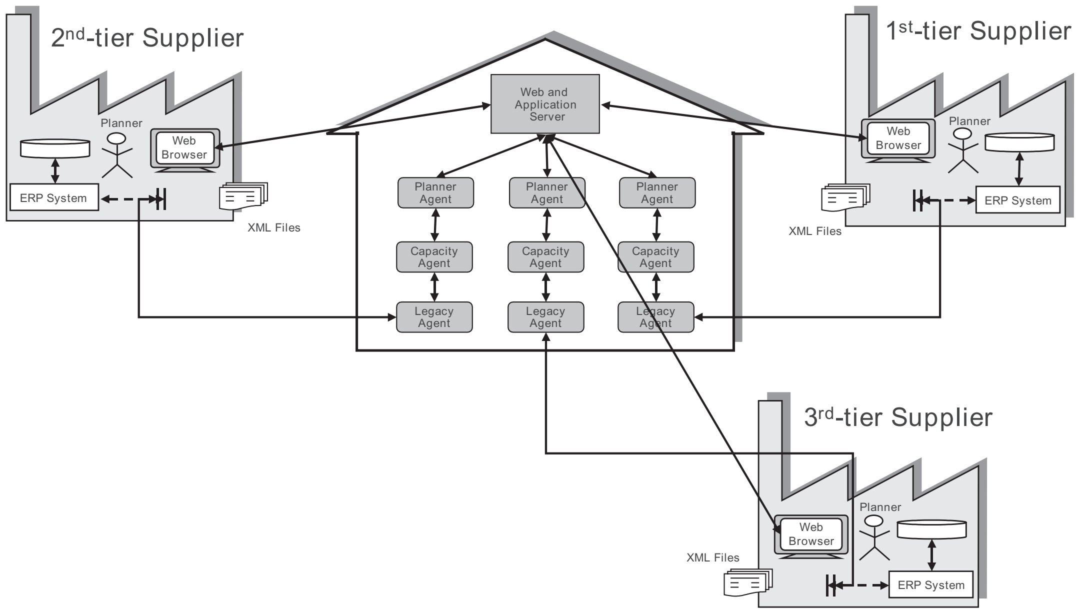

Figure 4. A simple configuration of the multi-agent system representing three business units.

downloaded from the web server, where the software agents were deployed, thus giving access to the user interface of the respective software agent. The web server exists purely to implement a download mechanism by which the JAVA applet is transmitted to the internet browser.

Both the software agents and their user interfaces were programmed in the JAVA programming language. The computational platform required to run the software is the JAVA 2 Standard Edition.

Communication between the user interface JAVA applet and its software agent is done throughout the remote method invocation (RMI) protocol over the internet inter-ORB protocol (IIOP).

The software agents themselves were developed on top of the services available in the FIPA-OS framework (Poslad *et al*. 2000). This is an open agent platform, previously delivered by Nortel Networks and presently maintained by Emorphia (http://www.emorphia.com). It is an Open-Source reference implementation of the Foundation for Intelligent Physical Agents (FIPA) open standards for agent interoperability (Aparicio *et al*. 1999). The framework, which is available in the Java computational platform, has been developed for constructing heterogeneous, multi-agent platforms, agents and services. It provides support for:

- different types of agent shells for producing agents, which can then communicate with each other using the FIPA-OS facilities;
- multi-layered support for agent communication;
- message and conversation management;
- dynamic platform configuration, multiple types of persistence and multiple encodings;
- abstract interfaces and software design patterns;
- diagnostic and visualization tools.

A great deal of effort was put on the design of the human–computer interaction. This was essential for two main reasons: from one side a clear and simple user interface was needed in order to allow the users to adequately explore the prototype functionality. In particular, it was necessary to hide the complexity of the capacity model regarding data structures and algorithms, both in terms of its own configuration and in terms of its operation. From the other side, the interface was designed in order to provide the users (planners) with all the information needed to make planning decisions concerning new orders evaluation. This information is presented through different types of graphical objects to better convey the time-phased nature inherent to this decision process. Relevant information types for this decision process are: available-to-promise data, inventory levels and capacity resources profiles.

Moreover, the user interface was designed to hide the internal agent-based behaviour, including the agent interactions, and to focus on the functionality, such that the system is viewed as a single decision support tool set up by the dynamic cooperation between the agents distributed by several network nodes.

5. Conclusions

Current available software packages in general do not provide the full support needed for networked and distributed organizations, and have clear gaps in what concerns the planning and coordination activities required in these heterogeneous environments. In order to overcome these drawbacks, the work presented in this paper proposes a *multi-agent system* architecture for real-time customer-order planning in distributed manufacturing enterprises, addressing the requirements of a *make-to-order* environment. The approach developed considers a full distributed architecture with real-time order negotiation functionality, available in each supply-network node, improving the global response time for new order requests and enhancing order-promising activities. Furthermore, the developed solution leads to a better management of the real production capacity considered along the whole supply network.

Several types of agents were designed that allow an easy configuration of the different distributed business units forming a cooperation network, as well as their cooperation processes. This system extensively uses the internet and will hopefully provide new and more powerful decision support tools to be used in distributed and virtual enterprises.

The multi-agent system has been installed and tested in three main nodes (Co-OPERATE pilots) of a dynamic supply network involving different sectors (automotive and the semiconductor industries). Although the preliminary experiences with the system prototype have clearly proved the potential of this approach, the growing importance of supply and cooperative networks obviously justifies further work in this area, namely in understanding the mechanisms of collaborative decision-making. On another direction, research is being pursued on negotiation planning procedures for improving network coordination, namely on dynamic interpretative rule-based systems, and on the complex multi-criteria decision-making processes involved in these problems.

Finally it should be noted that the capability of networked enterprises to dynamically change the type and strength of relationships between companies is a key requirement of information systems. But this is not a trivial issue in terms of design or implementation, and therefore deserves further research.

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