Software Agents-Enabled Systems Coalition For Integrated Manufacturing Processes and Supply Chain Management

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Abstract: Most business negotiations in supply chain and information exchange in manufacturing processes are heavily human-involved using proprietary data formats. The processes of negotiation and information exchange are usually time consuming and unreliable even in routine tasks. Software agents have been increasingly explored to improve the information flow and the decision-making process within networked manufacturing enterprises. In order to use agents in manufacturing applications, a software agent-enabled process integration framework for manufacturing and supply chain management has been developed and is described in this paper. The framework includes agent architectures, interaction protocols, message exchanges, an ontological engineering environment, business rules and knowledge bases, and databases. The initial implementation of the framework has been tested by a prototype multi-agent system in a steel product business network and a manufacturing network.

1 Introduction

The development of business and industry has led us to the situation where a single company cannot compete alone anymore. Pursuing effectiveness in operations has become a more and more important trend since the 1980's. The origins lie in industrial and international development [1, 2]. Markets are becoming more international, dynamic, and customer-driven; furthermore, customers are demanding more variety, better quality, and greater service in terms of reliability and response time [3]. Companies that are able to take a new approach to business and work closely with partners to design and manage processes that extend across traditional corporate boundaries will become more competitive; therefore, information management will be a critical enabler for the development of business networks - not only to automate the information utilization in an evolving way but also reengineer the business processes.

Because of these changes, we need to have different means in information-processing, which makes it possible to treat masses of customers as individuals and allow more and more companies to offer individualized products while maintaining high volumes of production [4]. Scale, cost, quality, and time are the paradigms where business is managed (see Table 1) [5, 6, 7]. The 21st century is bringing rapid innovation, driven by the continuing advanced technology boom and expanding global markets [8]. The accelerating rate of change will continue to be driven by the exponential growth and global availability of information, technologies, and technology-based infrastructure. A key factor to supply chain management (SCM) is the integration of processes in the supply chain – both upstream and downstream. The information and communication technology (ICT) has become an enabler for process integration. Operations in a supply chain are based on interaction and transmission of information; therefore, information and communication have had a significant role in business evolution.

Table 1 Criticality of information and communication - paradigms for success (European Quality)

	BEFORE 1980	**1980's**	**1990's**	**TODAY/ TOMORROW**
TO BE WINNER AT THE MARKET	PRODUCT QUALITY	CUSTOMER SATISFACTION	TIME TO MARKET	- balance expectations for all interest groups - continuous improvement in internal efficiency
TO STAY IN THE MARKET	COSTS	PRODUCT QUALITY	CUSTOMER SATISFACTION	TIME TO MARKET (ability to create added value for customers)
PRECONDITION FOR ENTERING THE MARKET	RIGHT PRODUCT	COSTS, RIGHT PRODUCT	PRODUCT QUALITY, COSTS, RIGHT PRODUCT	CUSTOMER SATISFACTION, PRODUCT QUALITY, COSTS, RIGHT PRODUCT

While the business environment has been changing in a revolutionary way, the technological development and the accessibility of knowledge have created new possibilities for enterprises towards open information exchange. Now companies can integrate their activities with their suppliers, customers, and partners by means of information technology. Specifically, the rapid development of the Internet and mobile network technologies has offered users, developers, and businesses new possibilities to collaborate, access and share information. The Internet appears to be a suitable infrastructure for business-to-business communication, which is predicted to become the most important application area of Internet technologies in terms of the market volume [9]. Internet infrastructure enables the use of software agents in Business-to-Business (B2B) solutions, and the agent technology has been considered as an important approach for developing industrial distributed systems [10, 11].

Agents can be utilized to further automate the supply chain management and reducing the amount of manual work. They can also assist in the automation of negotiation and engineering data exchange to increase the competitive position and profitability of a company in a business network. In manufacturing processes, agents support the integration of predictive models, process planning, and shop floor machining activities. Agents can also be used to encapsulate existing software systems to solve legacy problems and integrate manufacturing enterprise activities such as planning, scheduling, manufacturing execution, and product distribution; with those of their suppliers, customers, and partners into an open, distributed intelligent environment via networks [12, 13, 14].

In this paper, we present how agents and agent systems can assist in transmitting information within and between companies. We describe how a community of agents can make decisions and carry out tasks in a manufacturing network within a company or across companies in a supply chain. Our work is based on a business network architecture that is connected to enterprises' legacy systems by using agents. The business network of agents is being developed by the SteelNet project at VTT (Technical Research Centre of Finland) and the University of Oulu. The aim of the SteelNet project is to study the use of agents in industrial business networks by developing an agent-based prototype. A product design and manufacturing network of agents is being developed by the Process Integration Framework

(PIF) project of the Manufacturing Engineering Laboratory at the National Institute of Standards and Technology (NIST), an agency within the U.S. Government. Within the NIST research activities, agent communication is performed in a prototype multi-agent platform to demonstrate sharing of manufacturing knowledge and process data throughout the product lifecycle. NIST's work provides support for a variety of transactions among the business entities and among engineering activities within a company. NIST's multiple agents-enabled business and manufacturing systems coalition framework includes business and manufacturing networks, an ontological engineering environment, a multi-agent architecture, agent interactions, agent message format, and business rules. The first two components are discussed in this paper. The last four components have been described in [15]. Furthermore this paper introduces the business and manufacturing cases where the first prototype of business and manufacturing agents has been studied collaboratively by the PIF and SteelNet projects.

This paper is organized as follows: Section 2 reviews the current state of research in applying software agents to manufacturing and supply chain management. Section 3 describes an agent-based business and manufacturing systems coalition framework. Section 4 provides a structure of components in a multi-agent system. Section 5 presents agent communication networks. Section 6 proposes an ontological engineering environment that supports agent communication. Section 7 has an overview of our prototype implementations. Section 8 concludes the current work and outlines future plans. Acknowledgements and a disclaimer follow Section 8.

2 A Review of Software Agents in Manufacturing and Supply Chain Management

This section provides a brief review of the related literature in applying software agents to help companies to manage of manufacturing and supply chain activities. In the manufacturing area, agents are used to directly interact with existing (legacy) computer-aided design and manufacturing systems to enable these systems to be integrated with other systems in a manufacturing enterprise, such as scheduling systems, process planning systems, process optimization systems, design analysis systems, manufacturing execution systems, and manufacturing resource planning and acquisition systems. The CIIMPLEX project has developed an agent-based enterprise system to integrate design, process planning, and scheduling systems to enabling timely information flow among various departments in a manufacturing company [16]. The PIF project at NIST project has developed a multi-agent system to integrate machining process optimization software with a Numerical Control (NC) programming system to maximize material removal rate in machining processes [17]. The PACT project has developed a concurrent design environment using software agents to reduce design lead time and provide better communication among collaborators [18]. In the Intelligent Manufacturing Systems program, agents are used to implement a holonic manufacturing system to integrate manufacturing engineering software systems for intelligent manufacturing [19, 20]. Additionally, agents are also used in controlling production activities [21] and in representing machines to collaborate or compete with each other for jobs on a factory floor [22, 23, 24, 25].

In the supply chain management area, business-to-business transactions consist of several typically repeated chains of events, such as the requisition of resources, a request for quotes from candidate business entities, the selection of vendors, an order of enactment and delivery, and the relationship management among business entities. These events are relevant to functions of several business networks, including a strategic sourcing network, an electronic procurement network, a virtual enterprise network, a network of product design, manufacturing, inventory, and delivery management, a network of electronic marketplaces, a network for workflow/supply-chain management, and a network for supplier relationship management [26]. The use of autonomous and intelligent software agents has been studied in [27, 28, 29, 30] for easing this complex surrounding of business networks in electronic commerce. A multi-agent architecture has been developed to help decision-making in supply chain reengineering, such as help managers to understand costs, benefits, and risks associated with various alternatives [31]. An agent-oriented system has also been developed to allow agents that manage supply chain activities to interact with each other within a role-based organizational model to perform functions of negotiation, coordination, and acquisition in supply chains [32].

From our review, there lack a multi-agent framework for integrated manufacturing and supply chain management. This is needed by companies, both suppliers and clients, to be more efficient in production management, response to market changes, and price negotiation.

3 A Multiple Agents-enabled Framework for Business and Manufacturing Networking

In Figure 1 the companies are collaborating via mutually accessible information systems. The business network is connected to the company's enterprise resource planning system including the manufacturing network. The major internal activities in manufacturing companies are product engineering, manufacturing planning, and production management. The agents interact with engineering systems in design, planning, scheduling, and production management systems. Some of the agents retrieve data from databases and/or engineering rules from knowledge bases. These agents assist human engineers to build computerized models of products or processes, visualize data, and do scientific computations for making decisions.

Figure 1 goes here

Figure 2 shows a logical view of a multi-agent system architecture. A company network consists of many servers and Personal Computers (PCs). Servers include firewall servers, Web servers, and agent container servers. A Graphical User Interface (GUI) to agents is displayed on Web browsers in Personal Computers (PCs). A multi-agent system can also be integrated to a company's legacy systems and therefore they are transparent for the users. Agents are in several agent containers on servers, connected by a Local Area Network (LAN). The company LAN is connected to the Internet through a firewall within a firewall server. In practice, all companies have different network structures, since the companies vary from small engineering workshops to large corporations with hundreds of personal computers, servers and other systems networked together across far-reaching geographical locations. However, the basic principle is that the agent user interfaces are accessible from a PC and there is a firewall protecting the company network.

Figure 2 goes here

4. Components of a Multi-agent System

The main agent container in the agent platform provides a facility for agents of all the companies in the business network to communicate with each other. Additionally, the agent may register its capability and identification in the agent platform. The main agent container is located in a central server that is assessable via the Internet. The major functions of the agent platform include managing an agent joining in, logging out, and message exchange. Communication of the agents is secured by using the Secure Socket Layer (SSL) connection. The agents in this architecture are decentralized. Agents execute on an agent platform, which manages the messages between agents. The capability repository agent performs on the agent platform and uses a database for storing and retrieving the capability information about each agent that provides services. The agent platform manages the agent activities. The platform functions and components are largely based on the Foundation of Intelligent Physical Agents (FIPA) specifications [33]. The major functions include agent container management, message transport service, and agent directory facility. The messages sent by agents are dispatched and directed by the platform.

The component architecture describes the software components used in the agent-based integrated design, planning, and control system. Figure 3 shows the agents that are executed in the agent platform. The agents include a design agent, a group of process planning agents, a capability repository agent, and a manufacturing execution agent. Humans interact with the agents through the graphical user interfaces (GUI). The design agent communicates with a Computer-Aided Design (CAD) system to send and retrieve information about part design. A CAD system defines the shape and attribute information of a design of part components or an assembly.

Figure 3 goes here

Figure 4 shows agents in the process planning agent group. The process planning agent communicates with a Computer-Aided Process Planning (CAPP) system and a Computer-Aided Manufacturing (CAM) system to generate numerical control (NC) programs. CAPP software provides functions for selecting processes and resources and for generating process sequences. The NC software is used to create tool paths and NC programs for running computer numerically controlled machine tools. The agent sends and retrieves information about machining process planning to and from both CAPP and CAM systems. It also interacts with the tool material selection agent to select an appropriate cutting tool material based on the product attributes. The tool material selection agent selects the cutting tool material based on workpiece material, tool life requirements, and desired cutting speed. Tool material selection rules are stored in a knowledge base. The maximum material removal rate evaluation agent uses a mathematical model to calculate the maximum material removal rate based on the dynamics of the specific machine tool, the configuration of the cutting tool/tool holder/machine spindle, and factors in the machining process. The agent calculates an optimal set of cutting parameters, including cutting speed, feed rate, and depth of cut, based on the specific conditions. The tool life model agent has a mathematical model of the life of insert tools. This agent estimates the life of a selected tool, based on a lot size and coefficients derived from previously conducted tool-life experiments.

Figure 4 goes here

5. Agent Communication in Networks

Agents communicate with each other by exchanging messages. A message has two sections: message header and message content (also known as message body). The header contains the information regarding the sender, receiver(s), subject, date, and time that the message is sent by the sender, date and time that the message is received by the receiver, and the priority. In the sender or receiver information, there is a slot that contains the agent identification (AID). Using the AID, the information about an agent, such as its name, can be retrieved from a repository or agent directory.

The message content contains information regarding the intent. There are two types of content: illocutionary and perlocutionary. The illocutionary message is used to inform other agents, such as registering an agent's capability. The perlocutionary message is used to request actions of other agents, such as a request for machining process optimization or a call for proposal. Message content has the following attributes: an action verb, an object, preconditions, and constraints. The action verb is used to indicate the type of action to be taken by the receiver, such as request, propose, and query. An object is the result or expectation. Examples of classes of objects can be found in [34]. Classes related to the milling process have been applied. Preconditions are the properties that the sender may supply. Constraints are limitations with which expected results should be constrained. They are specified to provide information to the receivers to produce valid results. Agents must have intelligence to process messages. A body of knowledge supports the intelligence of an agent.

An example of agent communication in manufacturing network is shown in Figure 5. This interaction model specifies the timing and sequence of function calls – the interactions among agents. It shows interactions among agents for the scenario used in the integration framework. All the agents, except the process planning and capability repository agents, must first register their capability in the database. From the CAM system, the manufacturing engineer launches the process planning agent to determine and provide the optimal cutting parameters. Based on knowledge from the capability repository, the process planning agent obtains the tool material information by sending a request to the tool material selection agent. With this information, the process planning agent then determines an optimal set of process parameters based on analysis from both the machining stability perspective (i.e., highest material removal rate while maintaining a stable cut) and the cutting tool life perspective (i.e., recommended material removal rate to achieve specified cutting tool wear rate and tool life). With the result, the NC program can, therefore, be completed within the CAM system.

Figure 5 goes here

Figure 6 shows the interaction diagram in a business network where agents are exchanging information between companies. The sent information can be notifications on delivery such as information about schedules, changes, or a cancellation.

Figure 6 goes here

The source of agent intelligence is the knowledge base. This knowledge base contains rules that govern the agent behaviors. An agent's knowledge includes how to inquire about the capability of other agents and how to perform special tasks. For example, special tasks may include functions, such as tool material selection, machining stability analysis, or tool life evaluation. Basic rules for tool material evaluation can be commonly found in literature on process planning for metal cutting [35]. More specific and customized rules can be entered into the knowledge base. The rules are structured using propositional logic. The rules for both machining stability analysis and tool life evaluation are in mathematical form. The machining stability analysis is based on machining measurements and a machining chatter analysis and the tool life evaluation is based on the Taylor tool wear principle, and both methods are documented in the literature [36]. These two mathematical models are implemented using available mathematical software tools.

The manufacturing resource database contains information about the equipment and tools used in the machining process, such as data and attributes for the machine tools, cutting tools, and fixtures. The structure of the database is relational, and the database can be accessed by external programs via the Java database connector. In the database, a machine tool is defined by a set of attributes, such as the maximum power, the maximum cutting force in each axis, the maximum workspace dimensions, tool magazine information, the number of cutting axes, the maximum spindle speed, and available cutting tools. A cutting tool is defined by another set of attributes, such as tool identification, tool length, tool size, number of cutting edges, cutting angles on each edge, tool material, and tool overhang as mounted in its holder. Other resource information, such as for fixtures, workpiece materials, and operator skills, can also be stored in the database. An object model on machining resource information can be found in [37].

6 Ontological Engineering Environment

An ontological engineering environment is a set of methods and tools for humans to specify the meaning of concepts in a domain, the relationships between concepts, and the rules for extending and exploiting the domain-specific ontology. Our ontologies are restricted to supply chain management and manufacturing. Currently, the environment consists of ontology specification languages, language-processing tools, and an ontology edition tool.

The ontology for the SteelNet prototype describes basic concepts in the domain area and relationships among them. The Java Agent Development Framework (JADE) [38] compatible ontology was designed and implemented using the Protégé ontology editor [39]. In the PIF project the Web Ontology Language (OWL) [40] and Process Specification Language (PSL) [41] are used. OWL is used for specifying objects, such as tools, products, and machines. PSL is used for specifying business and manufacturing processes. Classes, properties, and constraints in OWL are used by agents to form their knowledge bases and a part of their messages. The authoring tool used is Protégé. The processing tool used is Jena [42], an application programming interface to OWL documents.

7 Implementations

In the manufacturing network, the multi-agent system has been tested with an example of a turned metal part. A process plan, selected tools, machining parameters, and a Numerical Control (NC) program were generated through the coordination of agents. The example part has outside features, such as grooves, neck, and cylindrical profile, and inside features, such as holes, rounded edge, and funnel, to be machined. Agents for process planning, tool selection, process parameter optimization, and machine tool control are initiated through Web access that provides a GUI for a user as an access to the multi-agent system. After starting a multi-agent system, the user can start agents. Human operators can monitor the message exchange of agents. An example is shown in Figure 7. A machining process simulation was performed, as shown in Figure 8. Details of the implementation are described in [43].

Figure 7 goes here

Figure 8 goes here

In the SteelNet project, a prototype application is being built for electronic supply chains by implementing agents for different roles in a business network. The first phase of the prototype implementation has been completed and includes a set of basic services and an application for a real-time tracking of heavy steel product manufacturing in a business network. The basic services are a web application server providing user interfaces, a user administration service, an alarm service, and an information service for companies to register their designing, manufacturing, transportation and inspection services to the business network's service repository.

The manufacturing follow-up application contains company and service-provider agents to share manufacturing-related data with each other using a well-defined ontology. The service provider agent provides secure data storage facilities for the company agents. Furthermore, the service provider agent notifies the company agents about events that they might be interested in, for example, a new manufacturing order in which the company is involved or a change of a schedule. The company agents inspect these events. If any abnormality occurs, they send alarms to the responsible users in the companies so that they can take necessary actions. For example, when there are delays in the manufacturing process, a company agent alarms the company's supervisor to re-arrange their internal work schedules, thus helping to reduce any undesired bull-whip effect and to maximize the utilization of their machinery.

In this first phase of prototype implementation, the company agents provide a web application that is used to update information in the system. The user interfaces are delivered by using standard Java Servlet and Java Server Page (JSP) technology-based web applications. Figure 9 presents an agent GUI to order products in a manufacturing company. The user interface shows information about an order, and its order lines and manufacturing processes related to them. The manufacturing states and estimated schedules are described with color codes, so users can quickly notice whether the manufacturing is on, ahead, or behind an agreed schedule.

Figure 9 goes here

The SteelNet prototype has been implemented by using the JADE agent platform. JADE was selected due to its use of the platform-independent Java programming language and compliance to FIPA standards for software agents [38].

8 Conclusions and Future Work

In this paper, we have introduced a software agent-enabled process integration framework, which exploits software agents in business network and distributed automation for manufacturing enterprises. By means of a prototype implementation, it is shown that agent technology can be used for information transmission and handling inside a company and between companies in a business network. It is also shown that it is possible to integrate these two multi-agent systems with the developed framework. Based on our implementations, it appears that the agent technology improves the accuracy, reliability, and speed of information flow, and thereby reduces internal costs in companies by cutting delivery cycles and enabling seamless information flow within a company and a business network. The greater potential of efficiency improvements lay in the fact that time has become a more and more critical factor in business. When automation makes the information transmission faster and also accurate, it actually is an enabler for possibilities that are not attainable otherwise. Agents assist the users of traditional industrial systems by executing the routine tasks of humans. This increases the speed and accuracy of information by eliminating human errors. The agents system can also provide alarms, which inform users automatically about unexpected changes in the supply chain.

The companies participating in the SteelNet project have tested the prototype application and its Web interfaces. The on-going work focuses on designing and implementing a framework to integrate it with companies' own legacy systems. In the near future the prototype will go through a field test, which will provide more valuable information for the development of the agent framework. Furthermore, enhancements are expected to provide additional capabilities and to address additional scenarios, based on collaborative efforts between NIST and VTT. For the NIST activity, initial specifications on agent messaging and agent interaction protocols for design and manufacturing will be developed and tested, building from the current implementations.

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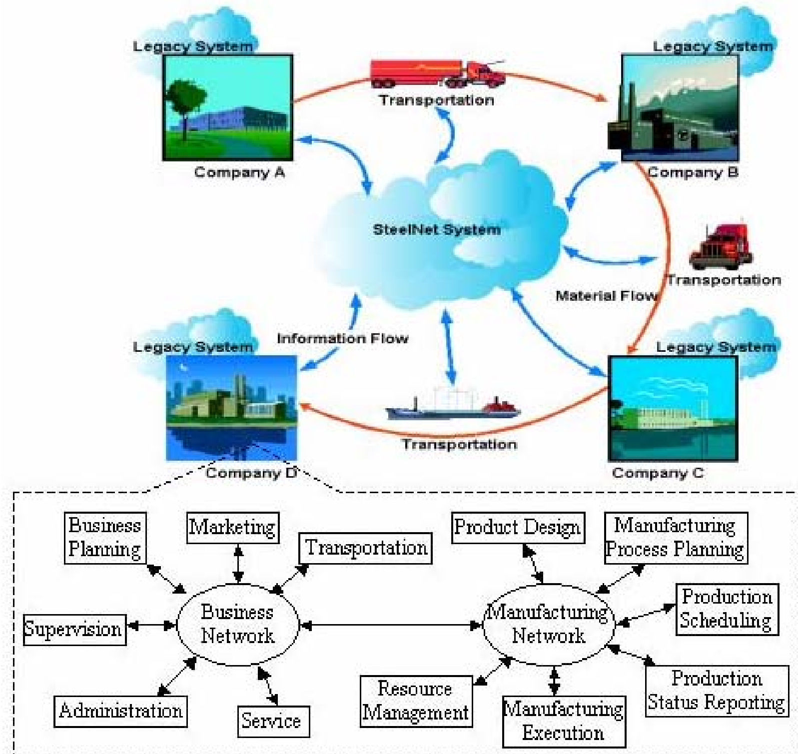

Figure 1 Business and Manufacturing Networks

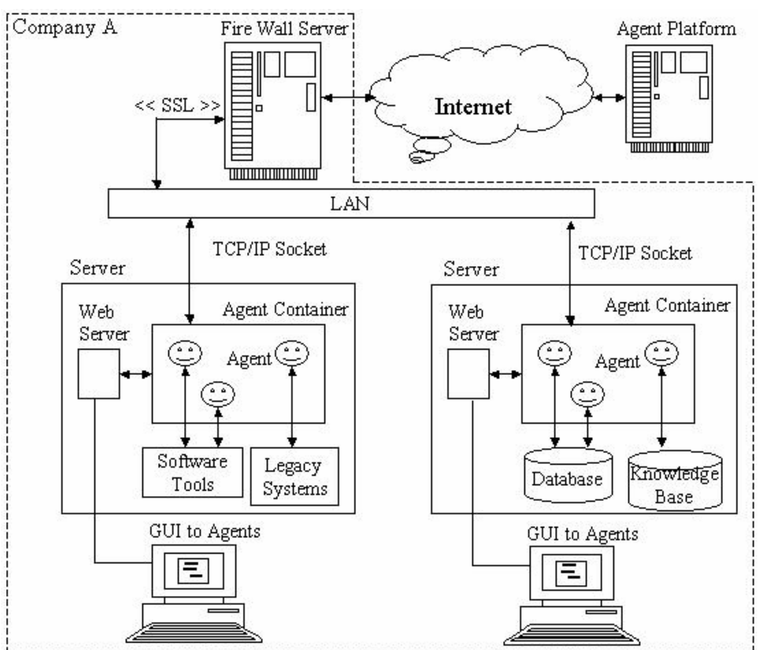

Figure 2 Logical View of Networked Agents

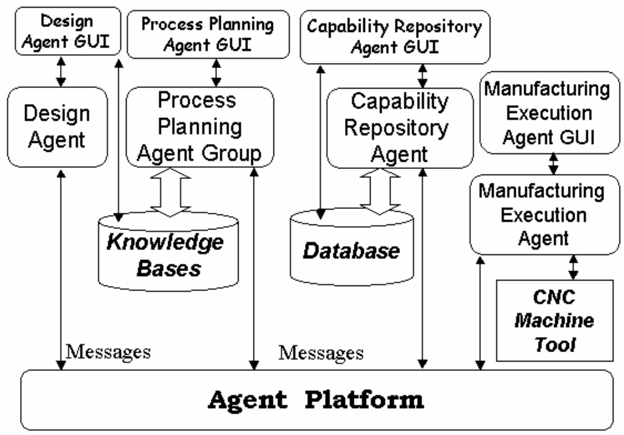

Figure 3 Multi-agent system architecture

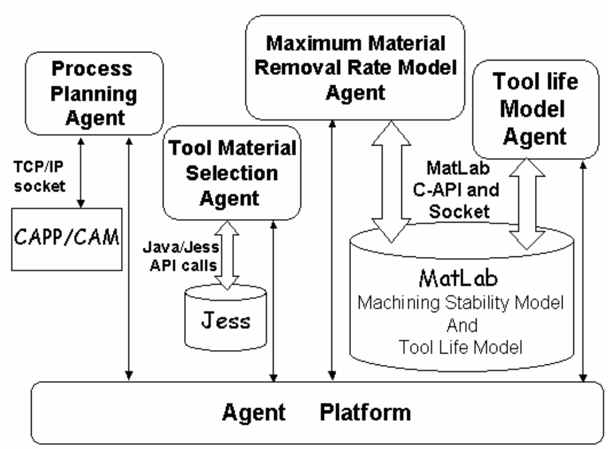

Figure 4 Process planning agent group

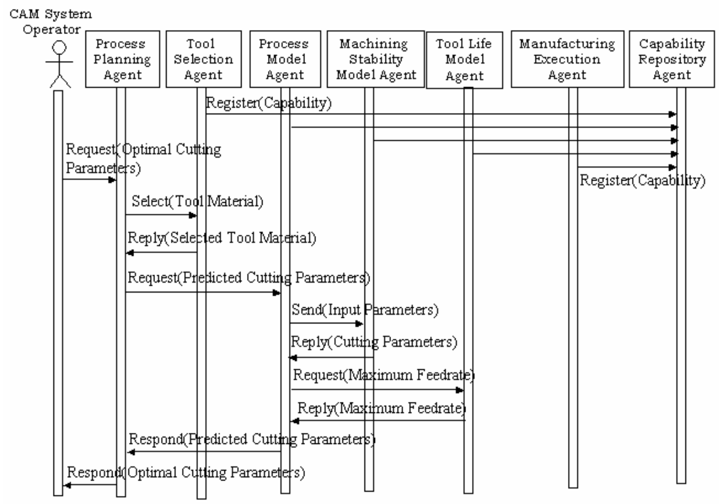

Figure 5 Agent interaction diagram

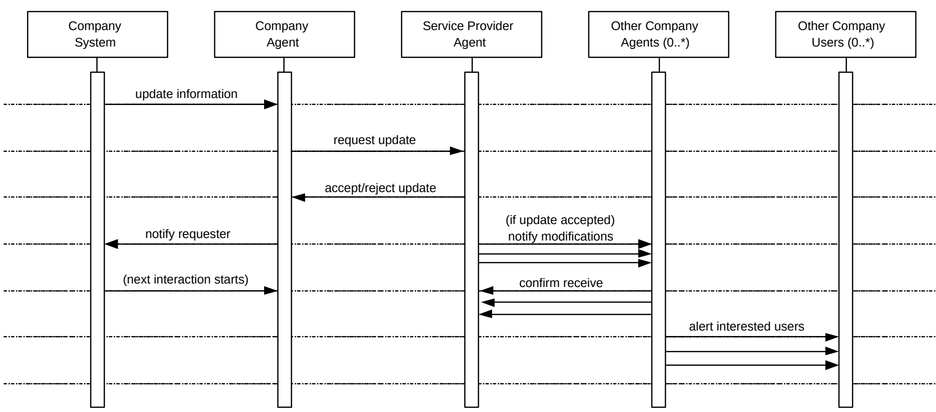

Figure 6 The interaction model in business network

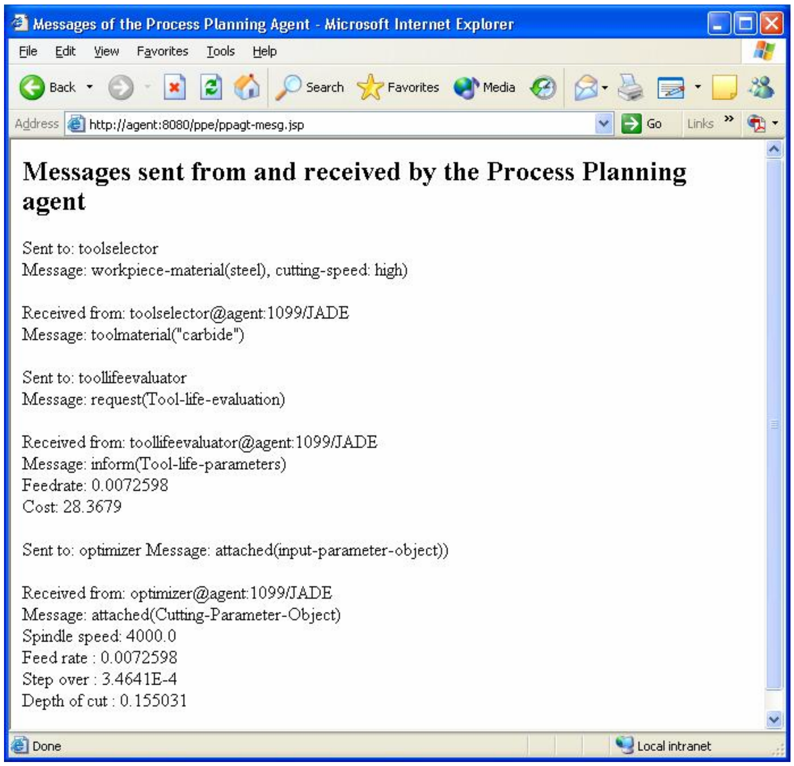

Figure 7 Messages of an agent

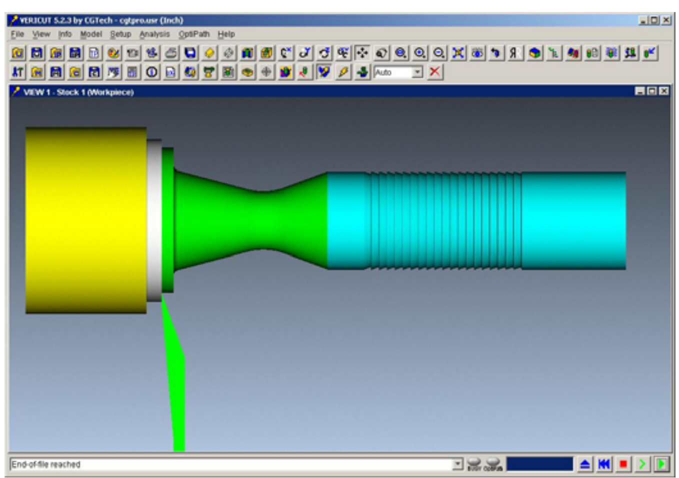

Figure 8 Machining Process Verification

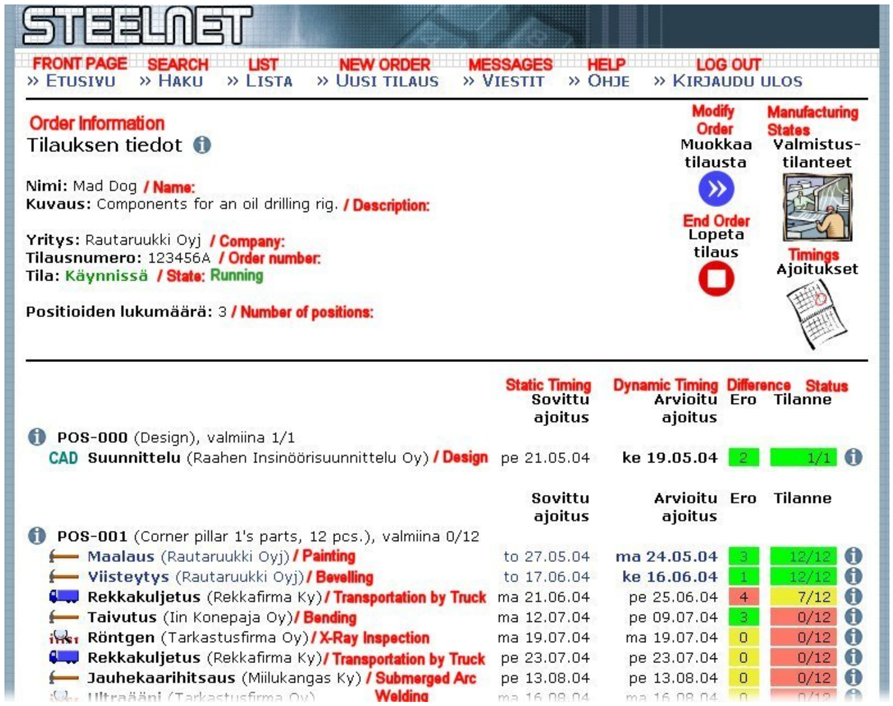

Figure 9 GUI of the SteelNet manufacturing agent showing an overview of a manufacturing process