Integrated Multi-agent-based Supply Chain Management

Daniel Frey
Institute for Process Control and Robotics, Universität Karlsruhe (TH), Engler-Bunte-Ring 8, 76131 Karlsruhe, Germany
frey@ira.uka.de

Tim Stockheim
Institute for Information Systems, University Frankfurt, Mertonstr. 17, 60054 Frankfurt, Germany
stockheim@wiwi.uni-frankfurt.de

Peer-Oliver Woelk
Institute of Production Engineering, University of Hannover, Schlosswender Str. 5, 30159 Hannover, Germany
woelk@ifw.uni-hannover.de

Roland Zimmermann
Department of Information Systems, FAU Erlangen-Nuremberg, Lange Gasse 20, 90403 Nuremberg, Germany
Roland.Zimmermann@wiso.uni-erlangen.de

Abstract

Multi-agent systems (MAS) offer new perspectives compared to conventional, centrally organised architectures in the scope of supply chain management (SCM). Their structure inherently meets the requirements of decentralised supply chains, whereas conventional SCM systems are often restricted in terms of dynamic behaviour, handling severe disturbances at supplier sites as well as dealing with highly customised or complex products. Since necessary data are not available within the whole supply chain, an integrated approach for production planning and control taking into account all the partners involved is not feasible. In this paper a MAS architecture integrating various intelligent agent systems is presented to address the problem.

1. Introduction

The goal of this paper is the introduction of a new supply chain planning and execution approach on the basis of multi-agent systems. Compared to existing SCM systems, the successful integration of numerous MAS that perform both inter- and intra-organisational planning and execution tasks is an important innovation.

Companies face a global market characterised by numerous competitors, a steadily increasing complexity of business processes and a highly turbulent production environment. The business processes have to be highly efficient and need to provide the necessary flexibility to be able to react to short-term changes of the customer demand and unforeseen events during fulfilment. Supply chains consist of networks formed by co-operating partners that are covering various companies (Original Equipment Manufacturers (OEM), suppliers, sub-suppliers, etc.). The global optimisation of the corresponding business processes offers a vast optimisation potential. On the other hand, various problems arise. For example, fluctuating demands multiply and create the so-called bullwhip effect. In addition, the global planning process is hampered by the fact that the companies are not willing to reveal their production data to competitors, unless they are forced to do so by powerful OEMs (as it is common in the automotive industry). This leads to the situation that a global optimisation is hardly feasible today.

MAS perfectly suit these demands for global flexibility, co-operation and, at the same time, local autonomy. The individual projects that are involved in the research activities presented in this paper address these problems and offer services in the range of SCM scheduling (DISPOWEB [1]), shop floor production planning and control (KRASH [2], IntaPS [3] and FABMAS [4]) and proactive tracking and tracing services (ATT/SCC [5]) to guarantee the reliability of supply chain processes in the case of unforeseen disruptions. In this paper, a reference model integrating the mentioned MAS is introduced including interfaces and gateways between the systems.

2. Integrated SCM Architecture

The basic scenario that is used to introduce the reference model comprises a simplified supply chain of a manufacturer of agricultural equipment (see figure 1). Its main value creation is due to the assembly of parts that it procures from different suppliers. In the scenario, a manufacturer of mechanical components and a supplier of seats are incorporated. The logistics service providers that are necessary to deliver the parts to the producer and to its customers are – although integrated in the figure – not yet considered in the integrated SCM architecture.

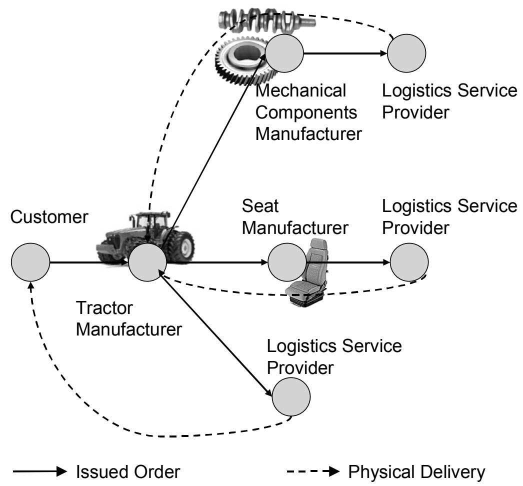

Figure 1. Supply chain scenario

The complexity of managing supply chains results in many different interdependent tasks such as the planning, execution and controlling of production, transportation and warehousing processes. As a consequence, multiple MAS specialising on certain tasks have to interact. The basic scenario focuses on production processes, whereas aspects of transportation can be integrated. Table 1 gives an overview on the various functionality of each MAS involved.

Table 1. Overview of MAS functionality

Main Functionality	Project
Negotiations between enterprises	DISPOWEB
Integrated process planning and scheduling (with focus on discrete manufacturing)	IntaPS
Production planning and controlling (with focus on assembling industries)	KRASH
Production planning and controlling (with focus on batch production)	FABMAS
Operational tracking of orders including suborders in supply chains	ATT*
Analysis of historical tracking information (tracing)	SCC*

** ATT and SCC are conducted in one project*

A logical starting point for a typical supply chain management cycle is the distributed global planning of supply chain activities. This is achieved with the DISPOWEB system. After generating an initial plan of orders and suborders concerning prices and time-points of delivery, software agents located at the different supply chain partners carry on negotiations. Thereby they optimise the costs and the due dates of deliveries (①, see figure 2).These optimised delivery plans are used on the intra-organisational level in each enterprise to plan the production of goods on each stage of the supply chain in detail. Three different multi-agent systems are concerned with varying aspects of production planning (②). They require the input from the DISPOWEB agents and generate detailed plans for their production facilities.

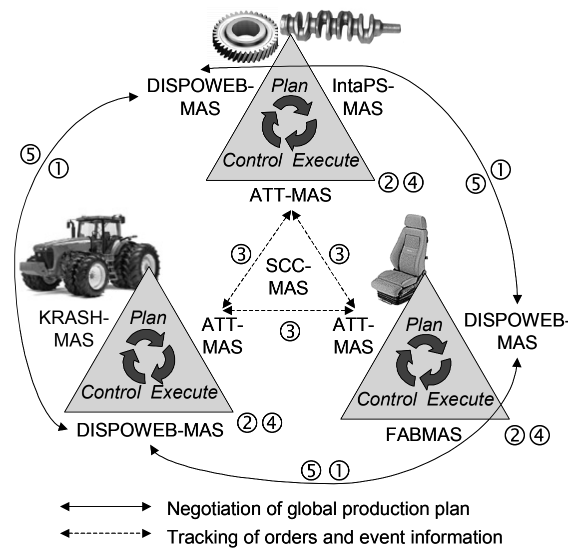

Figure 2. MAS interaction in the integrated SCM architecture

These plans are the initial input for a controlling system, which is developed in the ATT/SCC project. This multi-agent system monitors orders on every stage of the supply chain using a distributed architecture to proactively detect events that endanger the planned fulfilment [6]. In case of an event (e.g. a disruption in a production line) the ATT system is engaged in a communication with the related partner enterprises and informs them of the event (③). This output can be used as a trigger for rescheduling plans on an enterprise level (④) or, in case of major events, even in the re-negotiation of the contracts on the inter-enterprise level of the DISPOWEB system (⑤). An overview of activities and corresponding actors in the supply chain is given in table 2. In addition to the operational monitoring of orders, the ATT system communicates results of negotiations to a trusted third-party service called the SCC MAS. This agent system analyses the history of orders and their related sub-orders. SCC is able to identify patterns in the supply chain and order types that typically lead to problems during fulfilment. This information is both used as an input to enhance the tracking functionality of the ATT systems, as well as an input to the DISPOWEB agents that they can use for enhancing their negotiation strategies (e.g. demanding lower prices from suppliers with bad performance).

Table 2. Activities and Actors

Nr.	Activity (Actor)
①	Negotiate initial plan of production between supply chain partners (DISPOWEB).
②	- Operational assembly planning (KRASH). - Production planning for mechanical parts (IntaPS). - Production planning for seat production (FABMAS).
③	- Monitoring of orders and related suborders (ATT). - In case of minor critical events related partners are informed and internal planning systems are triggered (ATT). Next → ④ - In case of a severe critical event the DISPOWEB agents are triggered (ATT). Next → ⑤ - Routinely information is forwarded to trusted third-party SCC system (ATT/SCC).
④	Internal rescheduling in reaction to a critical event (KRASH, IntaPS, FABMAS). Next → ③
⑤	Renegotiate plan of production between supply chain partners due to severe critical event (DISPOWEB). Next → ②

3. Interfaces and Gateways

The architecture presented in chapter 2 describes the interactions of the single components of the SCM reference model, where each MAS provides a certain functionality. The exchange of data between the individual systems requires the definition of standardised interfaces and gateways that arise from the corresponding functional specifications.

The goal of the integrated SCM architecture is the co-ordination of the PPC (Production Planning and Control) activities throughout the whole logistics chain to realise a global monetary optimisation. Consequently, the definition of the interfaces is based on a PPC database structure. The technical specifications represented by database schemas are available at [7], whereas the UML (Unified Modelling Language) class diagram is presented at [8]. The following elements of the scenario's information view are mapped within the tables of the database (see figure 3):

- Master Data (including the bill of materials and the operation list for each product)
- Operation (assignment of machines to operations)
- Order (list of customer orders)
- Production Order (production plan generated by the PPC module)
- Disturbance Profile (disturbance profile for each machine)

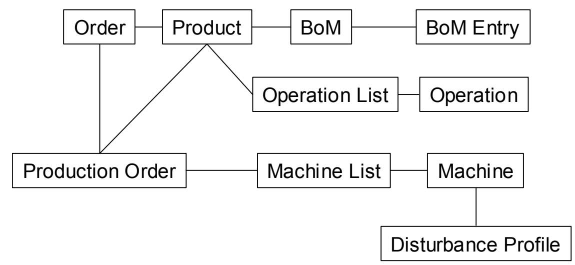

Figure 3. Database structure

The table *Product* contains product-specific data. The bill of materials (*BoM*) lists all parts that are necessary to assemble the product, whereas the operation list represents the single work steps of the product assembly. *Operation* is a table that is used to assign operations to machines that are able to perform a particular work step (including potential setup processes). The *Order* table lists all customer orders. Besides the product and the quantity, the due dates or starting dates of the orders are defined here. Based on the orders and the other parameters, the *Production Order* table records the results of the planning process (production dates, facilities, quantities). The *Disturbance Profile* table is machine-specific and is based upon disturbance histories gathered from an MDA (Machine Data Acquisition) or a PDA (Production Data Acquisition) system and rules of thumb.

This data structure is a significant component of the presented approach and serves as a basis for workflow integration within the supply chain scenario. The data structure is used both for the intra- and inter-organisational production planning. In the case of intra-organisational planning tasks, the order data serve as dynamic input to the planning process. The bill of material is analysed and, taking into account the operations and other parameters like the lot size or due dates, partial orders are assigned to single production cells. MAS-based planning algorithms perform the planning process within the projects mentioned in the first chapter.

In the inter-organisational case, order data and estimated completion dates are exchanged between the partners to realise an integrated production planning. The DISPOWEB agents need information about the load situation and completion times from the particular intra-organisational agents. The ATT systems are triggered with the information derived from the planning processes and then begin to gather information of the monitored orders (e.g. milestones, event data).

To enable the definition of content within the inter-agent communication, an ontology defining the necessary data concepts is required. An interface ontology has been designed, that was developed using a synthetic approach [9]. It integrates relevant concepts derived from the extensive domain-specific ontologies of the different MAS. The interfaces defined by the ontology are integrated into JADE and FIPA-OS, that were chosen as MAS-platforms. Specialised agents, which are capable to communicate using the interface ontology as well as the internal ontology of the particular system, serve as gateways between the individual applications.

4. Integrated SCM Scheduling

The DISPOWEB project is concerned with the creation of valid production plans as mentioned above. Each single partner is able to preserve its internal production data that is not crucial for the global planning process. Consequently, confidentiality concerns are taken into account, which may lead to a higher acceptance among potential industrial users [10]. To enable the accomplishment of a production plan comprising the whole supply chain, each factory has to be represented by a DISPOWEB agent.

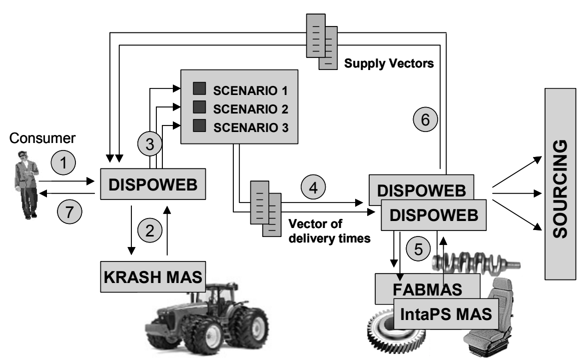

Figure 4. Supply chain scheduling

The generation of a production plan is initiated by the occurrence of an order (①, see figure 4) and accomplished step by step. Initially the tractor manufacturer, represented by an agent implemented in the context of the KRASH project receives the request for a product. The request is linked to a time-preference function and will be completely processed by the DISPOWEB agent involving the particular enterprise agent. DISPOWEB agents act as plan generators implying that the affected plan authority remains on the production agents' level. In the following, the planning process taking place between the DISPOWEB agents will be discussed briefly.

The DISPOWEB agent requests the KRASH agent for possible processing times and related costs for particular manufacturing processes (②). If not yet cached by the DISPOWEB agent due to former requests, task load information of the KRASH agent is required as essential information in addition. Picking up these information, the DISPOWEB agent begins to formulate a set of feasible planning scenarios (③). According to all scenarios, the latest possible delivery time for each required component or assembly is computed. The calculated results are submitted to the DISPOWEB agents representing suppliers (④). Within the scenario, the IntaPS agent and the FABMAS agent act as suppliers (⑤).

Having received such a supply request for a product, a DISPOWEB agent may ask other agents for the delivery of the required input products. An agent which does not depend on other suppliers or is able to fulfil the demand by stock liquidation replies by submitting a supply vector. Such a supply vector comprises the production costs as well as the load situation for the required resources. Receiving such a supply vector, a DISPOWEB agent verifies the existence of all supply vectors related to the required input products, i.e. those inputs, which are not available on stock. In case of completeness, the agent calculates its own supply vector for all potential delivery times starting with least possible production costs and finally sends them proactively to the DISPOWEB agent (⑥).

After having received all offers, the DISPOWEB agent at the end of the supply chain scenario computes the most profitable time for job execution with respect to the time preferences of the clients. The agent dispatches the job by transmitting selected delivery times to the supplier agents, implying the closing of a delivery contract between the parties. Having done that, the agent can contract with the consumer for the delivery of the product (⑦).

The mechanism is leading to an optimal solution for the orders that are accepted. To find an optimal solution in terms of accepting only the most profitable orders, the application of Combinatorial Auctions (CAs, [11]) is aspired. A downside of this proceeding is the need for higher preference revelation connected to CAs.

5. Integrated SCM Tracking and Tracing

Facing dynamic and uncertain environments, the fulfilment processes of production will often deviate from the initially planned production and delivery dates. In addition, inter-organisational information deficits concerning the operational progresses and disruptions in the fulfilment processes exist and lead to high costs of capital, unnecessary stock levels and prolonged cycle times. As mentioned in chapter 2, such deviations between the planned and the actual business processes and corresponding performance patterns are identified by the ATT/SCC MAS. The benefits are short-term improvements of the business processes through enhanced possibilities for reactions in case of disturbances.

At every partner site, an ATT MAS is implemented that follows the generic supply chain tracking algorithm depicted in figure 5.

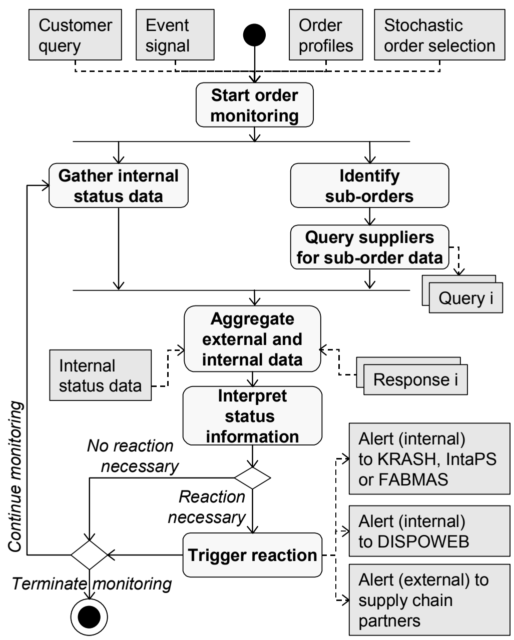

Figure 5. Generic supply chain tracking algorithm

The relevant order attributes and a scenario ontology, that describe the environmental conditions in the knowledge base of the software agents, is part of the architecture [12] and has been integrated in the interface ontology mentioned above.

In the case of a severe disruptions occurring in the supply chain, this event is reported to the corresponding DISPOWEB MAS. Thus, the planning system is able to react to the modified constraints and proposes a new schedule. If this is not possible, a rescheduling of the affected sub-processes is done.

For this purpose, the delay of the contract is propagated to the downstream DISPOWEB agents at the suppliers' sites. These eliminate the tasks from the production schedule of the respective production systems. Thereupon a new assignment is initiated by the DISPOWEB agent at the tractor manufacturing site trying to fulfil the according task as soon as possible, in order to minimise the delay. The result is the closest feasible solution to a Pareto-efficient solution for all supply chain partners.

6. Flexibility and Reliability

Manufacturing systems have to provide flexibility and reliability to stay competitive. Multi-agent systems are expected to be more flexible than centrally organised systems. In addition special mechanisms integrated into the SCM reference model ensure the reliability of the MAS.

Three features make sure that the flexibility and reliability of the supply chain is guaranteed.

1. Flexibility of the decentralised SCM algorithms.
2. Integration of proactive tracking and tracing methods into the reference model.
3. Reliability of the decentralised local shop floor PPC algorithms.

Features one and two have been discussed in chapters 4 and 5. The reliability of the shop floor planning systems is the basis for higher-level reliability of the SCM system.

On the intra-organisational level KRASH, IntaPS and FABMAS offer MAS-based PPC functionality. In the scope of the presented supply chain reference model, the shop floor MAS architectures perfectly match the requirements defined above. The statement, that MAS are more flexible and reliable than common centralised systems, can be verified using realistic benchmarking scenarios. The throughput times of productions orders were analysed, whereas both the medium throughput time and its standard deviation were checked. The planning process was performed by a reactive MAS approach on the one hand and a common OR algorithm on the other hand. The evaluation shows, that the suitability of the PPC MAS depends on the frequency of disturbances. Nevertheless the standard deviation for the MAS was permanently lower throughout the whole evaluation process.

Figure 6 visualises that fact. Values larger than 0 (scaled comparison factor representing the probability of MAS, respectively OR algorithm performing better) represent scenarios where the MAS is superior to the OR approach. It is obvious that this statement is valid for this example. The results even improve with an increased planning complexity of the scenario (equals a decreasing lot size in this example) (for further information concerning the OR algorithm and the evaluation process refer to [13]). Constant (at least a small standard deviation) and thus predictable throughput times are a prerequisite for high quality results of the DISPOWEB planning MAS. Along with the ATT-MAS, this reliability on the operational level takes care of the overall reliability of the integrated SCM architecture.

A potential disadvantage of the architecture is the increased communication and co-operation effort. This question has to be investigated in the next phase of the priority research program by testing the implemented

MAS using realistic test case scenarios (for further information, see [14]).

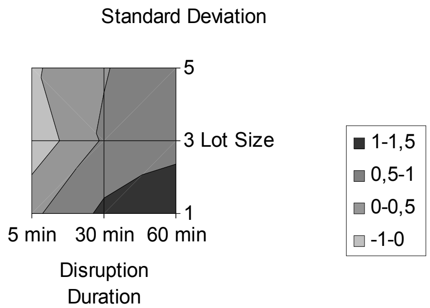

Figure 6. Suitability of a MAS approach with respect to the standard deviation of the throughput time

7. Summary

In this paper, a MAS-based SCM approach is presented. It addresses the architectural, the planning and the execution aspects of supply chain management. Besides the functional requirements like an integrated SCM scheduling, non-functional requirements like the reliability and the flexibility of the system are also met.

The reference architecture and its interfaces and gateways are tested on the basis of a test case scenario. The goal of the evaluation is to prove the feasibility of the approach and gather first experiences and results. In the next step, the system will be evaluated using a real test case scenario that represents an industrial scope and the corresponding complexity.

One instantiation of the database structure presented in chapter 3 is available at [15]. The supply chain that was chosen represents a tractor manufacturer and its suppliers. Due to the closeness of the test case to the automotive industry, the transfer of the results to a broad spectrum of applications is guaranteed.

8. Acknowledgement

The research projects mentioned within this paper are funded by the Deutsche Forschungsgemeinschaft (DFG) within the German priority research program 1083 “Intelligent Agents in Real-World Business Applications” (refer to http://www.realagents.org for further information).

9. References

[1] DISPOWEB project, “Dispositive Supply-Web-Coordination”, *[Internet]*, Available from: http://www.dispoweb.de/ [Accessed 13.3.03]

[2] KRASH project, “Karlsruhe Robust Agent Shell”, *[Internet]*, Available from: http://www.ipd.uka.de/KRASH/ [Accessed 13.3.03]

[3] IntaPS project, “Integrated Agent-based Process Planning and Production Control“, *[Internet]*, Available from: http://www.intaps.org [Accessed 13.3.03]

[4] FABMAS project, “Agent-Based System for Production Control of Semiconductor Manufacturing Processes“, *[Internet]*, Available from: http://www.realagents.org/public.php?ID=915 [Accessed 13.3.03]

[5] ATT/SCC project, “Agent-based Tracking and Tracing of Business Processes”, *[Internet]*, Available from: http://www.wi2.uni-erlangen.de/research/ATT/index-e.html [Accessed 13.3.03]

[6] R. Zimmermann, R. Butscher, F. Bodendorf, A. Huber, and G. Goerz, “Generic Agent Architecture for Supply Chain Tracking”, *2nd IEEE International Symposium on Signal Processing and Information Technology ISSPIT 2002*, Marrakesh, 18-21 December 2002, pp. 203-207.

[7] DB Specifications, “DB Specifications on RealAgentS”, *[Internet]*, Available from: http://www.realagents.org/public.php?ID=901 [Accessed 13.3.03]

[8] UML Class Diagram, “UML Class Diagram on RealAgentS”, *[Internet]*, Available from: http://www.realagents.org/geturl.php?ID=1053 [Accessed 13.3.03]

[9] C.W. Holsapple and K.D. Joshi, “A Collaborative Approach to Ontology Design”, *Communications of the ACM*, Vol. 45, No. 2, ACM Press, New York, 2002, pp. 42-47.

[10] T. Stockheim, M. Schwind, O. Wendt, and S. Grolik, “Coordination of Supply Webs based on Dispositive Protocols”, *10th European Conference on Information Systems (ECIS)*, Gdañsk, 6-8 June 2002.

[11] M. Schwind, T. Stockheim, and S. Seibel, “Price Controlled Resource Allocation For The Provision Of Information Products And Services Employing Combinatorial Auctions”, *11th European Conference on Information Systems (ECIS)*, Naples, 2003 (accepted).

[12] R. Zimmermann, S. Käs, R. Butscher, and F. Bodendorf, “An Ontology for Agent-Based Monitoring of Fulfillment Processes”, *Workshop Proceedings “OMAS Ontologies for Multi-Agent Systems” at EKAW02*, Siguenza, 30 September 2002, pp. 81-96.

[13] D. Frey, J. Nimis, H. Wörn, and P. Lockemann, “Benchmarking and Robust Multi-agent-based Production Planning and Control”, *7th IFAC Workshop on Intelligent Manufacturing Systems IMS 2003*, Elsevier Science Ltd., Budapest, 7-8 April 2003 (accepted).

[14] RealAgentS, “Real Agent Scenario”, *[Internet]*, Available from: http://www.realagents.org/ [Accessed 13.3.03]

[15] Tractor database structure, “Instantiation of the test case database structure”, *[Internet]*, Available from: http://www.is-frankfurt.de/tractor/ [Accessed 13.3.03]