38

PROCESS PLANNING AND SCHEDULING WITH MULTIAGENT SYSTEMS

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This paper deals with the approach of application of intelligent software agents to improve information logistics in the area of process planning and production control. Thus, enterprises will be able to fulfil the requirement of flexible, reliable and fault-tolerant manufacturing. Fulfilment of these requirements is a prerequisite for successful participation in modern business alliances like supply chains, temporal logistic networks and virtual enterprises. Thus, agent-based improvements of information logistics enable enterprises to face the challenges of competition successfully. Current research activities focus on the development of agent-based systems for integrated process planning and production control. They led to the "IntaPS" approach, which is presented in this paper.

1. INTRODUCTION

Since the last decade is characterized by far-reaching changes in global economy and liberalization, modern management trends such as just-in-time manufacturing, or reduction of vertical range of manufacture are of increasing importance to realize shortened time-to-market and a more flexible consideration of customer' demands. However, modern industrial products are often characterized by a high complexity of design, functionality and necessary manufacturing and assembly processes. Computer systems for the support of process planning, production control, and scheduling tasks have to handle critical paths, bottlenecks and risk of failures within real-time. On the one hand, this situation provides the opportunity for small and medium-sized enterprises (SME) to improve their competitiveness within global economy. They participate in supply chains and form virtual enterprises to fulfil specific customer demands. On the other hand, the ability to perform efficient handling and processing of all necessary information is of increasing importance.

Thus, so-called "information logistics" is one of the crucial factors for business success of enterprises. This paper presents the approach to improve in-house information logistics in the field of process planning and scheduling by the application of intelligent software agents.

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2. SITUATION IN THE APPLICATION DOMAIN

2.1 Existing Challenges in the Application Domain

Companies participating in supply chains and virtual enterprises have to meet several requirements such as providing a specified product at a defined time to the customer reliably. Since customers will switch to other contractors for their orders in future if their requirements are not met (e.g. by repeated delivery delay), unfulfilled requirements will weaken the market position with a lasting influence. From a holistic point of view ("top-down point of view"), the supply chain as a whole is as efficient as the weakest "link", respective an inefficient enterprise. Thus, each enterprise aims to reach a high economic viability and to become a strong and reliable link of the supply chain. Therefore, it is important to take all necessary organisational measures to keep estimated manufacturing costs and due dates as well as to meet contracted quality of the product. One of these organisational measures deals with the improvement of internal information logistics, because availability of information is a crucial factor for modern enterprises in a dynamic environment.

This challenging situation is enforced not only by dynamic behaviour of the supply chain itself but also by other trends in modern product design and manufacturing. It effects internal structures of the enterprise ("bottom-up point of view"). For example, customers demand highly customised products even in serial production ("mass customisation") which leads to a large number of variants. Thus, modern manufacturing systems must be able to handle several products and variants with small lot sizes simultaneously. Furthermore, modern products are characterized by a high complexity of design. They take advantage of an integrated design of mechanical, electrical and information processing components ("mechatronics"). In conjunction with innovative product design, manufacturing processes need to be improved as well. These optimisation procedures depend on information about constraints and suitable parameters of all involved manufacturing processes (Tönshoff & Siebert, 2001). Thus, improvements of internal information logistics are not only a demand resulting from the holistic point of view of the supply chain as a whole. From a bottom-up point of view, these improvements are necessary for every modern manufacturing system, too. Consequently, modern manufacturing is in need of new and innovative concepts for improved information logistics.

2.2 Current Situation in the Area of Process Planning and Production Control

With respect to the manufacturing domain, attention has to be drawn to process planning and production control. The traditional approach of separating planning activities like process planning from executing activities like production control and scheduling is characterized by strong borderlines. These borderlines result in a gap between involved systems which implies a loss of time and information. This situation becomes obvious for example in the strict spatial as well as temporal separation of process planning and production control. In most cases, static linear process plans are used for information exchange. Thus, the current situation in industrial application is characterised by several disadvantages like:

- Information about capacity and current load of resources as well as further economic aspects remain disregarded while generating conventional static process plans.
- In case of unexpected events like machine breakdown, missing devices or tools etc. at the shop floor, process plan modifications are carried out on shop floor level. This will lead to feasible, but not to optimal results. On the other hand, modifications carried out by a centralised process planning group are very time-consuming.
- Complexity of manufacturing processes and the knowledge necessary for process planning increase. Due to well-trained workers, this knowledge is available at shop floor level mostly. It often takes a long time until this knowledge is available at a centralised process planning group.
- Due to the lack of knowledge exchange, quality and reliability of planning results will be reduced on a long-term basis.
- Advantages of the application of innovative manufacturing technologies, which are often more suitable regarding ecological aspects, remain unused.

Since it is indispensable to improve information logistics in process planning and production control, several research activities tried to find suitable solutions. A very promising approach is the use of multiagent systems. Ongoing research activities at the Institute of Production Engineering and Machine Tools, Hannover, focus on this field and are carried out in cooperation with the Center for Computing Technologies, Bremen. These activities led to the "IntaPS" approach.

2.3 Existing Approaches to Overcome Known Limitations

2.3.1 Integration of Process Planning and Production Control

The aim of integration of process planning and production control functionality is well known for several years. Since the end of the 1980ies, several research projects worked on this problem, but most of these projects based on centralised system architectures and used approaches like bulky, non-linear process plans, e.g. the EC joint-research projects FLEXPLAN and COMPLAN (Tönshoff *et al.*, 1989, Kruth & Detand, 1992). Current research activities use flexible process plans for scheduling of flexible manufacturing systems or apply AI techniques to improve the procedure of process planning (Teti & Kumara, 1997). A very interesting approach ("EtoPlan") is presented by Kals, Zijm and Giebels (Giebels *et al.*, 1998, Giebels, 2000).

2.3.2 Application of Software Agents in the Manufacturing Domain

Very interesting and promising developments deal with intelligent software agents to improve information logistics in the manufacturing domain. First applications of multiagent based concepts are implemented yet. Most of these applications aim at scheduling problems and resource allocation like the "MAPS" system (Wellner & Dilger, 1998). "MAPS" is a multiagent production planning system, which was part of a joint-research project called "INKAD". The system comprises functionality for middle-term and short-term scheduling with regard to the current shop floor situation as well as an interface to communicate with a commercial PPC system ("Production Planning and Control"). Further approaches focus on applications with a less detailed but wider scope like plant design, inter-enterprise relationship and supply-chain management.

Another important application is the design of "Holonic Manufacturing Systems" (HMS). The idea of HMS is promoted by an international IMS research project ("Intelligent Manufacturing Systems") for instance. A "Holon" is an autonomous and co-operative building block of a manufacturing system. It consists of an information processing part, and can also contain a physical processing part or even a human being. Thus, the concept of holons has a wider scope than a pure intelligent software agent. Furthermore, a holon can be part of another holon. Thus, the presence of hierarchies (called "holarchies") is a basic concept of HMS. Furthermore, a holon may belong to more than one holarchy at the same time which is an important difference to the traditional concept of hierarchies. A very comprehensive overview of holonic scheduling technologies is given by L. Bongaerts (Bongaerts, 1998). Current HMS research activities at IFW focus on holonic scheduling algorithms (Zwick & Brandes, 2001).

3. AGENTBASED ARCHITECTURE FOR INTEGRATED PROCESS PLANNING AND PRODUCTION CONTROL

3.1 Basic Architectural Concepts of the "IntaPS" Approach

Since most applications of software agents in the manufacturing domain focus on planning and scheduling tasks from a logistic point of view, the main topic of the current research project "IntaPS" is set to agent-based integration of process planning and production control. Thus, technological information about various products and product variants are handled in addition to economic information in a very flexible and distributed way.

Since the application of co-operative multiagent systems (MAS) and intelligent agents seems to be very promising, MAS also open up risks for the safety and security of enterprises and the robustness of the (distributed) production. The security issues associated with agents in real-world industrial applications fall into three major groups: integrity attacks, privacy attacks, and denial of service attacks. Therefore, it is necessary to establish adequate security mechanisms (e.g. certification mechanisms for dynamic trusted relationships in supply chains) or to restrict MAS to trusted cooperation partners only (e.g. "rational agents" and "closed markets"). Recent research deals with the first issue, but for implementation of MAS in today's production processes, it seems to be necessary to apply the latter security approach and to restrict MAS to trustful participants.

The "IntaPS" approach is based on the application of co-operative agents and in-house electronic marketplaces. The basic architecture of "IntaPS" consists of two substantial components, which link information systems of earlier stages of product development and the resources on the shop floor (see Figure 1). This link is realised by decentralised planning on shop floor level and by rough level process planning.

3.2 Decentralised Planning Unit on Shop-Floor Level

A multiagent system implements decentralised planning on shop-floor level. The co-operative agents act very closely to the shop floor and have access to production data at any time. Within this architecture three different types of agents are used, resource, order, and service agents.

Each relevant resource of the production system and its environment is represented by an *resource agent*. In contrast to a "Holon", the real world entity is not part of the artificial concept of the agent. Agents exist for e.g. machines, assembly workplaces, transportation devices as well as virtual resources like business information systems, CAM systems for NC code generation or legacy information systems. Resource agents provide local knowledge bases of associated resources. The entirety of all resource agents represents the shop floor model of the whole production system.

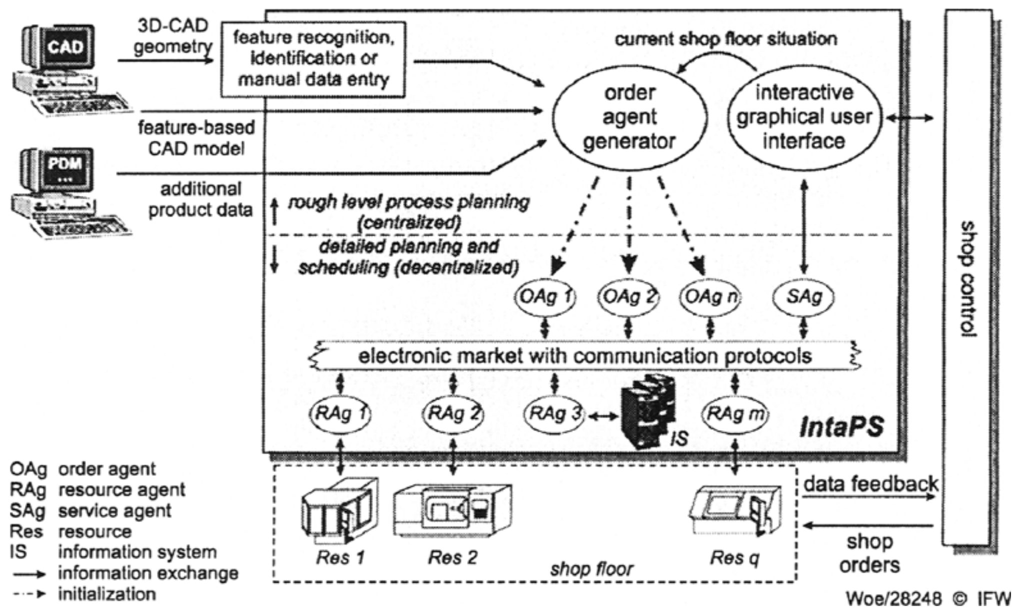

Figure 1 – Basic architecture of the "IntaPS" approach

Order agents represent orders for manufacturing and pursue the goal of market-based optimisation (i.e. optimise utility functions representing their individual goals). Different order agent types vary in divergent weights of goals within their utility functions: An order agent representing a rush order will rate the goal "finished on scheduled due date" higher than the goal "using cost-efficient manufacturing processes", for example. An order agent representing a stock order should prefer the opposite weight of goals. Thus, the individual utility function is used to evaluate possible action alternatives of the order agent. Since lead times in single or small-batch manufacturing of high-sophisticated products may be very long compared to mass production, boundary conditions of the production environment can change significantly. Thus, orders are represented by agents, not as passive objects resources have to work on. Due to their autonomy and pro-activity, purposeful acting order agents recognise these changes and are able to react appropriately and reorganise their plans and goals if necessary.

Service agents are used for human interaction, transparency and maintenance purposes. Thus, human users like process planners are enabled to track actions performed by agents and to interact with the system. Users can inquire for information concerning the status of current orders or the system's performance. Processes hidden inside the agent system are made visible and comprehensible. Furthermore, the user is able to adapt the system to new boundary conditions e.g. by generating new resource agents in case of putting new machines into operation at the shop floor. Some service agents perform system monitoring tasks and will request user interaction under particular conditions, e.g. if the knowledge of some agents is insufficient or if the agent communication comes to a "deadlock situation" which has to be solved by external intervention.

The detailed process planning and scheduling takes place co-operatively within an electronic marketplace, which is realised as a "closed market" due to the security issues above. Order agents and resource agents are interacting according to a "three-phase-model":

- Communication on required manufacturing skills, due dates, capabilities, and capacities results in identifying of suitable sequences of manufacturing. The optimal sequence of manufacturing operations is accepted as a detailed plan ("negotiation phase")
- Order agents examine continuously whether detailed plans are executable under the current conditions to ensure the feasibility of plans ("verification phase").
- If necessary, order agents tender parts of the detailed plan for new auctions. The improved alternative detailed plan substitutes the previous plan. Afterwards the verification phase is resumed and lasts until the order is finished ("re-negotiation phase").

Since "IntaPS" focuses on internal coordination of an enterprise, it does not contain particular agents to represent customers or products as known by the HMS architecture. Only information about the product and customer demands, which are relevant for the manufacturing process, are passed to the order agent during initialisation. All other information about products and customers would increase the amount of necessary communication for the MAS and may lead to a reduced performance of the system. Nevertheless, product agents and customer agents are useful to represent supply chains or customer relationships. In these cases, a workshop, a plant or a whole company may be represented by e.g. a resource holon, which has to deliver a specific product to a specific customer in time. The internal structure of the resource is immaterial in this case, but a system based on the "IntaPS" architecture may be used for this purpose.

The electronic marketplace as well as the agents of the JAVA-based "IntaPS" prototype implementation are realised using a FIPA-compliant agent platform called "FIPA-OS" (Buckle, 2000). In addition to standardised components of the agent platform, further enhancements (e.g. adaptive communication protocols and knowledge representation) are part of the "IntaPS" project (Timm *et al.*, 2001).

3.3 Centralised Rough-Level Process Planning

The second essential component of the "IntaPS" approach is the centralised rough level process planning which processes the incoming data and generates a rough process plan in the context of a rough planning. These data are geometrical or technological information about the workpiece (e.g. from CAD systems) as well as further organizational information related to products and orders (e.g. from PDM or ERP systems). Order agents are instantiated with respect to these information and to current production data like machine skills and load. After their instantiation, order agents possess a rough level process plan which defines their scope and contains geometrical, technological and organisational information. The rough level process plan only contains information which the agent is not able to recognize from its environment. Examples for this kind of information are manufacturing features, which have to be processed during manufacturing, constraints between separate manufacturing operations (e.g. compelling manufacturing sequences) and constraints with other orders. Thus, order agents get all necessary information for decentralized detailed process planning and scheduling and obtain a maximum scope for the allocation of suitable resources and time slots for manufacturing.

3.4 Modelling of the Application Domain

One important aspect of "IntaPS" is the structured modelling of the application domain. Thus, a modified modelling method based on "MAS-CommonKADS" (Iglesia *et al.*, 1998) has been used for this purpose. This method consists of three phases: Conceptualisation, Analysis, and Design. During the first phase called *Conceptualisation*, the analysed domain is examined from a user-centric point of view. Typical use-cases are identified as well as some basic communication requirements. The objective of this phase is to get a basic idea of relevant interaction between participating entities. The results of this phase a documented using UML charts (Use-case diagrams, Message-Sequence-Charts) and will be refined in the second phase.

The second phase is called *Analysis* and results in five mostly formalised detailed models which serve as a basis for prototype implementation. These five models are:

- *Organisational model.* Description of the organisational structures in which the MAS has to be used (in this case: process planning department and shop floor of an enterprise) such as hierarchical structures, relationship between agents and their environment and agent society structure, identification of agents and roles.
- *Task model.* Determination of goals of the individual agents and their tasks.
- *Agent model.* Detailed model (e.g. represented as a UML class diagram) and (semiformal) textural description of the agents.
- *Coordination model.* Model of the agent interaction and coordination including specification of suitable communication protocols (e.g. based on state diagrams and detailed sequence message charts).
- *Expertise model.* Modelling knowledge of the domain, agents and environment.

These models are represented in UML mostly. Some descriptions of individual agent properties contained in the agent model are based on a semiformal textual patterns.

The last phase is called "Design" and deals with detailed design of the agents as well as the agent platform respective the electronic marketplace. Thus, the third phase leads to implementation activities for realisation of the MAS and in our case to the "IntaPS" prototype.

In context of the expertise model the „Ontology Inference Layer" (OIL) is used for specification of an ontology which is common to all agents participating in the electronic marketplace. Thus, formalisation of necessary knowledge for rough-level process planning as well as for decentralised detailed planning is an important task of the "IntaPS" project. Therefore, common information models of the manufacturing domain are analysed (see Figure 2). Relevant information as well as other information concerning the domain are represented by three major information models: product model, resource model and process model. For example, appreciable information models are: a formal description of manufacturing features from ISO 14649 "STEP-NC" (e.g. as a basis of negotiations between order agents and resource agents and as a basis for time calculation for resource agents), product structure definitions based on ISO 10303-4x "STEP" and a classification of manufacturing processes according DIN 8580.

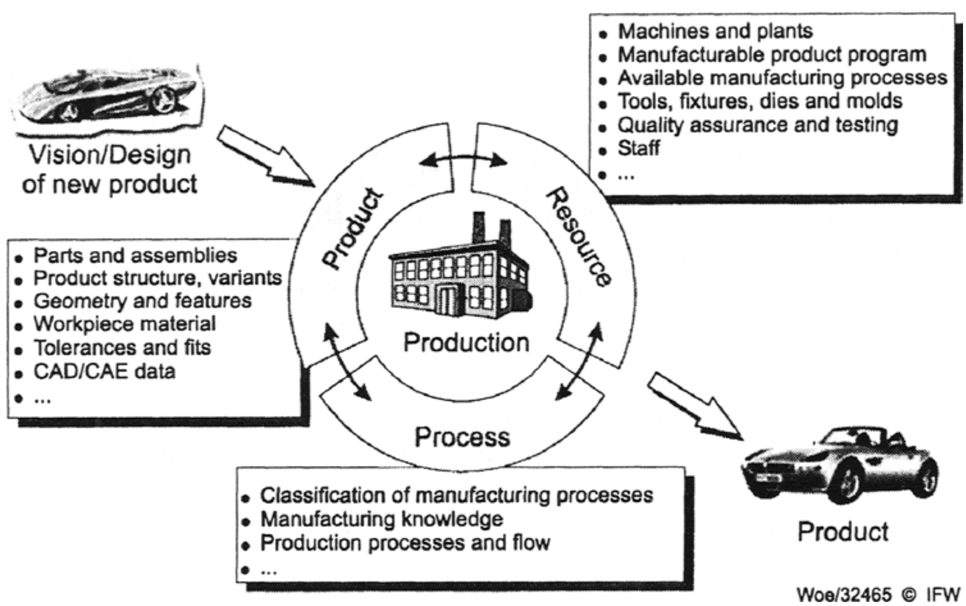

Figure 2 – Relevant information models in the production engineering domain

4.3 Evaluation Concept

The evaluation concept for the "IntaPS" prototype implementation is based on reference data sets which are part of a realistic scenario. They contain technical information about the products and orders (e.g. data of manufacturing features) as well as economic and logistic information like due dates and order quantities. Reference data sets will be processed in two different ways: With conventional tools as well as using the "IntaPS" prototype. Using conventional tools (see Figure 3, left side), sets of static process plans will be created using a standard process plan editor and scheduled by a conventional scheduler. The scheduled manufacturing orders are "manufactured" in a simulated ("virtual") shop floor environment. The "virtual" shop floor will be realized using "Tecnomatix eM-Plant" (former "SIMPLE++"). Simulation results are logged by "eM-Plant" and will be used for statistical analyses.

In addition, the same reference data sets will be processed using the "IntaPS" prototype. Therefore, the "IntaPS" systems communicates with the "virtual" shop floor using a TCP/IP connection and the TCP/IP socket interface of "eM-Plant". Thus, the MAS serves like a "remote control" for the "eM-Plant" simulation. As in the first case, "eM-Plant" logs all relevant events and simulation results. Finally, statistical data like average and maximum load of resources, lead times or delay of delivery will be compared and evaluated.

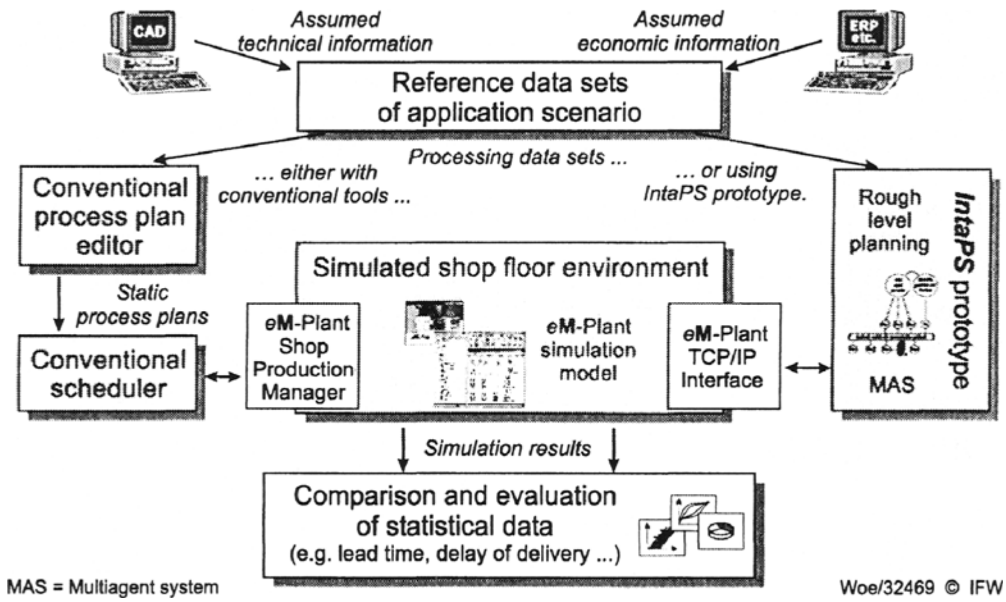

Figure 3 – Evaluation concept for the "InaPS" prototype

The reference scenarios used for evaluation purpose are not only used for the "IntaPS" project. They are specified using a document structure which is very similar to the FIPA template for application specifications. Since the "IntaPS" project is part of a German priority research program and all projects of this program agreed to use a FIPA-compliant specification to describe their scenarios, a library of several scenarios is under development and will be available at end 2003. On a long term basis, the application scenarios of the priority research program will lead to FIPA-compliant application specifications. Some aspects of the "IntaPS" approach are specified according to patterns which are used for agent-oriented software engineering, too.

5. SUMMARY AND OUTLOOK

This paper proposes a system architecture based on the application of co-operative agents for optimising information logistics in the field of process planning and production control. Due to the approach of a wide integration, capacity information and due dates will be taken into consideration for early stages of process planning. On the other hand, process planning knowledge will be used for short term scheduling decisions at the shop floor. Therefore, problems will be eliminated which result from time-delayed return of manufacturing knowledge and capacity data or other lacks of information flows e.g. from the use of static process plans.

Our current research activities deal with a structured application domain model which is a representative sample of a real-world production system. The evaluation is based on a prototypical implementation. Further developments are planned for a second project phase starting in summer 2002. Some of the addressed topics of "IntaPS-2" are enhancements for co-operative manufacturing (e.g. subcontracting of single manufacturing process steps). Since the current shop floor model is capable to represent job shop production only, "IntaPS-2" will consider integration of principles like manufacturing islands which may lead to hierarchical structures in the multiagent system.

6. ACKNOWLEDGEMENT

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