ExPlanTech: Multi-Agent Framework for Production Planning, Simulation and Supply Chain Management

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Abstract. We present a unified multi-agent technology for decision making support in production planning and scheduling, manufacturing simulation in and supply chain management. The technology has been tested on several industrial cases and is used in a daily production planning processes of one important automobile industry supplier in the Czech Republic.

1. Introduction

In the cases of highly flexible production process, the proper production planning can highly increase its effectiveness. On the other hand, the high flexibility makes the production planning and acquisition of relevant data quite complicated.

There is strong demand for universal and flexible tool for the production planning that is able to increase utilization of resources and supports a decision making in a selection of orders. The flexibility of the tool should allow to adapt the system to changes in the production structure, or to allow using the system by another customer. The system should use a universal description for all resources, including product design and development, production, stores and transport. The system has to be able support not only internal production processes, but also integration of external business processes and universal secure access to the data.

We focus the production planning having a need of following elements:

- **Existing software integration** – the already existing software solutions, which can be still exploited, can be integrated into new system.
- **Complex data representation, collection and maintenance** – the production data and its flow are complex process. There is strong demand to collect, store and use existing data in the most suitable way,
- **Extra-enterprise access** – the need of access the production data anytime from anywhere is required.
- **Supply-chain integration** – not only access, but also integration of the outside processes is needed. Linking the suppliers, customers and other collaborators is very crucial problem.
- **Security** – all the parts of the system have to use the appropriate security politics. The factory business data are very important and have to be properly secured.

- **Visualization** – complex data and production processes generates the need of centralized view. This view has to be adjustable to the user and have to be accessible from the place, where the user needs to see the information.
- **Emulation and simulation** – not just planning problem is solved in the complex production. The simulation of the processes helps to find better configuration of the production, and recognize and analyze the possible problems.

The needs of the nowadays enterprises cannot be covered by classical solutions anymore. New technologies that deal with all the requests described above have to be adapted. In the next part of the text we present the ExPlanTech multi-agent technology of the production planning.

1.1. Multi-Agent Technology

Agent technologies and the concept of multi-agent systems is coming from the field of artificial intelligence and computer science, using principles of component-based software engineering, distributed decision making, parallel and distributed computing, autonomous computing, advanced methods of interoperability and software integration. Operation of an agent-based system is based on interactions of autonomous and loosely coupled software or hardware entities – agents. The computational processes which are characterized by natural decomposition or possible computation distribution can be solved by multi-agent systems very well [4]. Moreover, the multi-agent system offers superb run-time integration capacity and dynamic reconfiguration, and autonomous delegation abilities. They are robust and provide easy integration of humans, existing software and hardware.

Agents technologies are suitable for domains that posses either of the following properties:

- highly complex problems need to be solved or highly complex systems to be controlled,
- the information required for solving problems or controlling systems is distributed and is not available centrally,
- in domains with dynamically changing environment and problem specification, or
- high number of heterogeneous software (and possibly hardware) systems needs to be integrated in an open and heterogeneous way.

There are several typical application areas of the agent technologies that relate to manufacturing [8]. In production we need highly complex planning problems to be solved, we need to control dynamic, unpredictable and unstable processes. In production there is also a potential for agent-based diagnostics, repair, reconfiguration and replanning. In the domain of virtual enterprises [1] and supply chain management there are requirements for forming business alliances, planning long-term/short-term cooperation deals, managing (including reconfiguration and dissolving) supply chains. Here we also can use various agent technologies for agents' private knowledge maintenance, specification of various ontologies and ensuring service interoperability across the supply chain. In the domain of internet-base business agent technologies can be used for intelligent shopping and auctioning [5], information retrieval and searching, remote access to information and remote system control. An

important application domain is logistics. Multi-agent systems can be used for managing transportation and material handling, optimal planning and scheduling, especially in cargo transportation, public transport but also peace-keeping missions, military maneuvers, etc. There is a nice match of the agent technologies and managing of the utility networks such as energy distribution networks, mobile operators networks, cable provider networks. Here the concept of distributed autonomous computation can be used for simulation and predication of alarm situations, prevention to black-out and overload and intrusion detection.

2. ExPlanTech Technology

ExPlanTech is a consolidated technological framework that is an outcome from the series of European Union RTD and Trial projects in the area of agent-based production planning [10]. ExPlanTech is a collection of different components, which can be put together in order to develop a custom-tailored system for supporting user's decision making in different aspects of production planning.

From the user perspective the system is supposed to provide the support to the human user when sizing resources and time requirements for a particular order, creating the production plans, optimizing manipulation with material resources, managing and optimizing the supply chain relationships, visualizing and analyzing the manufacturing process in middle and long terms and accessing the data from outside the factory.

ExPlanTech system provides technological support for easy software integration, complex data representation, data-collection, maintenance, extra-enterprise access, supply-chain integration, security handling, visualization and emulation/simulation, while it does not feature at the moment any agents or components for control and real-time diagnostics.

As a result of used multi-agent architecture, each software system based on ExPlanTech concept is component-based, flexible, and reconfigurable and allows distributed computation and flexible data management. Each component has been integrated in an agent wrapper that complies with the FIPA (Foundation for Intelligent Physical Agents) standard for the heterogeneous software agents [3] and can be used in a variety of configuration or independently as a standalone application. System configurations can contain various planning, data-management or visualization agents. An agentification process can be also used for an integration of the software and hardware equipment already existing in the enterprise.

Another advantage of agent-based approach is its ability to process relevant production data, distributed across the entire enterprise. The classical approach when data are collected and processed centrally is difficult especially in situations where the production planning data are voluminous and changes frequently. Agent approach allows to process data proactively at the place of their origin and to exchange only necessary results. The agent-based technology certainly does not provide an uncomplicated solution of NP-hard planning problems. However the concept allows integration of heavy-duty AI problem solver (such as constrain satisfaction systems, linear programming tools, genetic algorithms, etc.)

An agent technology is also suitable paradigm to integrating the manufacturing enterprises into a supply chain. From the planning perspective it is irrelevant whether the system reasons about in house manufacturing workshop or about a subcontracted company.

Production managers are often interested in modeling and simulation of the production process. Experimenting with changes in production lines, and how they affect the manufacturing process as a whole, is not a trivial task but it can be simplified by ExPlanTech build in simulation environment.

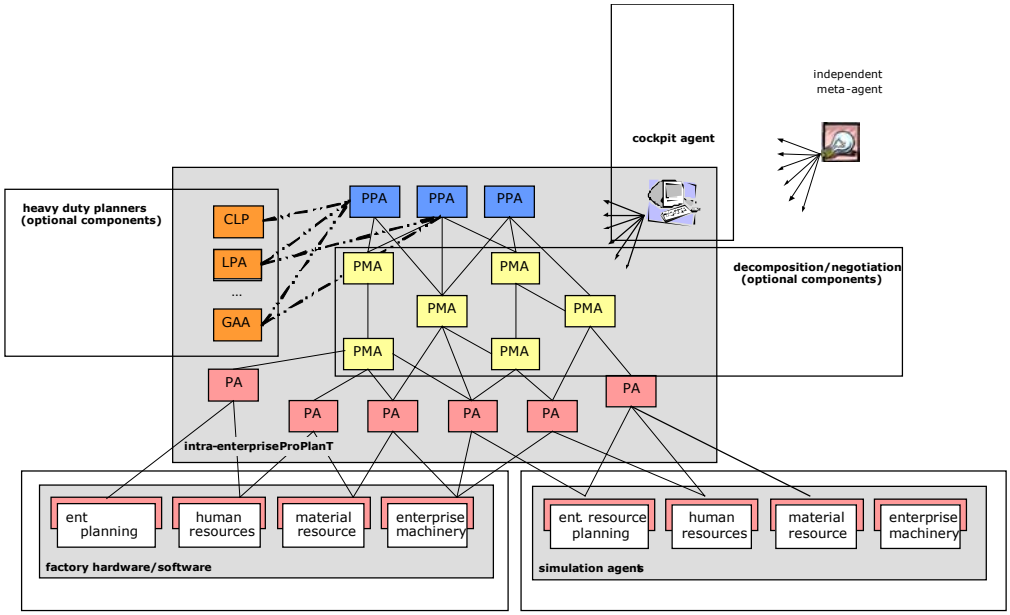

Fig.1. ExPlanTech Intra-Enterprise Architecture

2.1 ExPlanTech Architecture

The ExPlanTech framework is build on top of JADE (Java Agent Development Environment) [6,2], the most wide spread agent integration platform that provides full FIPA interoperability [3]. An appropriate ontology for semantic interoperability in manufacturing domain has been developed within the ExPlanTech development. Fig. 1 shows ExPlanTech intra-enterprise architecture and the following part describes the most remarkable agents present in that architecture.

Planning Agent

The core of the any ExPlanTech based system is a community of appropriate planning agents. The planning agent is in charge of making production plans for individual orders, taking care of conflicts and managing re-planning and plan reconfiguration. For different types of production, different planning engines are available or can be developed:

- **Linear planning:** For planning problems with limited computation requirements, caused by limited plan variability, or restrictive external constrains (e.g. predefined priorities or ordering), a backward/forward chaining based planning engine exists.
- **Mathematical programming:** For cases with an explosive variability of possible plan configurations, an existing engine based on the linear programming method can be extremely efficient under specific situations. For other hard problems, constrain-satisfaction or genetic-algorithm based planning engines can be developed. These methods and engines are however very specific and would need to be re-developed for new planning cases.
- **Distributed planning:** At the same time planning can be implemented collectively by a community of simple planning agents. The plan (especially if multi-criteria optimization needs to employed) would be constructed by be sophisticated auction-based negotiation based on use of the social knowledge and acquaintance models.

Resource Agents

Typically, there are many resource agents running in the system that carry out data gathering and specific data pre-processing and that directly interact with the planning agent. We provide two types of agents for an integration or representation of manufacturing resources. ExPlanTech features (i) agents that integrate/simulate a specific machine, workshop or department (e.g. CNC machine, CAD department) and (ii) agents that integrate a factory software system (e.g. an implemented bridge to MRP system that administers material resources handling in the factory).

Cockpit Agents

There may be several different users interacting with the planning agent at the same time. In order to allow such an access and to control possible conflicts, we have developed a specific agent – a cockpit agent. The cockpit agents presents the user in a user friendly way with the state of production processes, plans, loads of given resources etc. Cockpit agent also provides a possibility to interact with the system, and according to access rights change the plans or resources parameters.

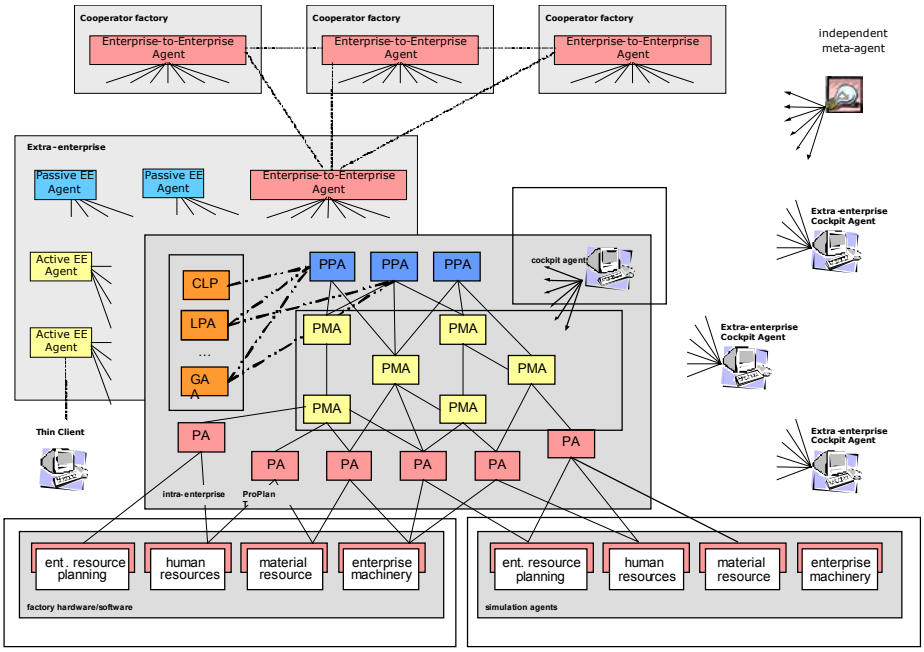

Fig.2. ExPlanTech Extra-Enterprise Architecture

Extra-Enterprise Agent

While Cockpit Agents are intended to be used inside the factory (and inside a security firewalls of the factory), the Extra-Enterprise agents allow an authorized user to access the system from outside using a thin client technology (see Fig. 2). As the environment outside the factory is variable, also the technology for Extra-Enterprise access must be very flexible and platform independent. To satisfy this requirement, an Extra-Enterprise agent has been developed [11], that can, in cooperation with application server, made ExPlanTech system accessible via the WEB browser, PDA device or WAP-enabled phone. Secure connection protocol and a system of user access rights protects the system against an unauthorized access [7].

Enterprise-to-enterprise Agent

As the Extra-Enterprise agent makes the system accessible for authorized human users outside the factory, the Enterprise-to-enterprise agent makes it accessible for external software systems (see Fig. 2). These external systems can be for example Remote Cockpit Agents that represents thick clients for a remote access. In addition, the Enterprise-to-enterprise Agent (E2E agent) can proactively connect external agents (such as similar E2E agents in another factories or agents of material resources suppliers), exchange data with them and use them for decision support. This technique can help to find possibilities of tasks outsourcing in case of exhausted local resources, can advertise local free capacities to the cooperators or can search for optimal suppliers of material resources.

Simulation Agent (ExPlanTech Real-Time Planning Simulation)

For the purpose of evaluation of plans by modeling a feedback from a plan realization, it is possible to simulate the behaviour of the real production. The simulation agent represents an interface between the planning system and a community of emulation agents. The emulation agents substitute the real machine or human resources and model their properties such as production times or failure rates. They follow production schedule defined by plans while adhering to the common simulation times and speeds defined by the user. Consequently they provide a feedback to the planning system by means of the simulation agent, announcing the actual time spent on a plan realization to the planner. If the actual time differs from the plan, the planner initiates a re-planning. The agent-based architecture of the simulation offers modularity of the whole model, so it is possible to replace each emulation agent by an agent with another parameters or by a binding to the real resources. On the other hand it is possible to provide the same emulation with another scheduler.

Meta-Agent

Meta agent operates differently on different levels of the system operation. Within the intra-enterprise level the meta-agent carries out sophisticated methods of meta-reasoning in order to independently monitor the information flow among the agents and suggest possible operation improvements (e.g. workflow bottlenecks, inefficient or unused components in the production process, carry put long term performance measurements, etc.) On the extra-enterprise level the meta-agent is designed to provide centralized knowledge about communication among selected extra-enterprise agents – companies integrated in the supply chain. Its goal is to ask other agents for their communication logs on regular basis, to store the collected information in its local database and thereby to provide an entry point to a further analysis or visualization in the attached user interface. The meta-agent employs the same security module as ordinary extra-enterprise agents, thus it strictly conforms the same security rules.

2.2 On implementation

As mentioned above, the ExPlanTech system is implemented using the JADE multi-agent development environment. This decision affects many features of the system and implicates many assets of the ExPlanTech platform. In the following some examples of these assets will be briefly discussed.

The first advantage of the JADE platform mentioned is not directly visible to the end user, although it influences whole the system – JADE development environment is easy to use and allows rapid development of sophisticated and reliable multi agent system. Predefined agent core with already implemented control and message transport protocols frees the author of MAS from low-level programming and resource management. The designer can focus on high level functions and can easily build user targeted application.

The second advantage has also been already mentioned. Any application build on JADE platform complies with FIPA interoperability standards for implementing of independent software agents [3]. This feature facilitates an easy integration of new and third party components to the system as well as use of independent meta-agents for communication evaluation and optimization.

JADE platform and thus whole ExPlanTech system is implemented in JAVA2 language which gives to it a platform independence and openness. Agents can run on different platform (MS Windows, Windows CE, LINUX, even PLC) and cooperate without care of low level platform specific problems. The same implementation of the agent can be used on different platform.

JADE platform contains sophisticated open system for communication support. Agents can use various message content languages to serialize interchanged data. In ExPlanTech system, three different languages are used for different purposes: JADE native SL0 language is used for common intra enterprise communication. XML language is used for extra-enterprise communication, where the human readability is more important and bit efficient BEC language is used for communication with embedded devices, where the amount of transmitted data must be kept low. JADE also uses two models of addressing – intra-platform and inter-platform. When the intra-platform addressing is used, the agent is identified by its unique name and the AMS (Agent Management System) agent is responsible for finding of the receiver on computers, connected to the agent platform. When the inter-platform addressing is used, the agent's identification must contain a valid address in some message transport protocol (IIOP, HTTP, etc.) and AMS agent uses an appropriate protocol to deliver the message to an computer outside the agent platform. In ExPlanTech system, all computers inside one factory are organized as one agent platform and so all intra-enterprise communication uses intra-platform addressing. Extra-enterprise communication uses inter-platform addressing and HTTP protocol.

For an implementation of application server for ExPlanTech thick clients, a Tomcat server developed within Jakarta project of The Apache Software Foundation was used. Tomcat server uses so called Servlets or a JSP (Java Server Pages) technology to generate documents. Servlets are special Java classes, that are invoked when a request for a document comes, and those generate the document. ExPlanTech thin client Servlets utilizes the JADE agent ability to directly communicate with another application, running in the same JVM (Java Virtual Machine).

3. ExPlanTech Use Cases

There is a set of the most usual ways, how to utilize ExPlanTech based system:

3.1 Production planning, dynamic re-planning

The most obvious use case is intra-enterprise planning production planning. The ExPlanTech provides sets of linear and non-linear plans and schedules of in-house manufacturing activities that are to be carried out so that the requested orders and tasks are achieved while utilization of the enterprise resources is optimized. Given the fixed deadlines the system provides the user with resource requirements and an appropriate manufacturing schedule. If there are insufficient resources available in order to meet the deadline, the users get notified, and a supervised process of re-planning and re-scheduling is initiated. Re-planning in ExPlanTech is often a reaction to the situation when the planning problem dynamically changes (e.g. by malfunction of the manufacturing machinery). Re-planning thus solves existing or potential conflicts in production plans. ExPlanTech provides sophisticated tracking of interdependence among the particular tasks which makes re-planning process very fast and prevents from planning again from scratch.

ExPlanTech continually analyses the production data in order to give a feedback to the project planner and to keep the plans up-to-date. Task specifications and resources capacities can be changed any time and new plans are re-computed and displayed in real time. A so-called “competitive planning” allows examining of several possible orders, testing their feasibility and choosing of the best one.

3.2 Supply Chain Management

In order to solve a complicated task of an automated supply chain management, many technical and commercial difficulties have to be overcome. Unlike in the case of the intra-enterprise planning, ExPlanTech has not a complete knowledge about supplier’s parameters and capacities. This is why the simplest “master-slave” interaction approach is not sufficient and classical auctioning techniques (e.g. contract-net-protocols) are provided by ExPlanTech system. In addition ExPlanTech handles secure and authenticated communication by the X-Security component, and it uses the concept of acquaintance models in order to handle temporal suppliers inaccessibility. For supply chain integration and management ExPlanTech provides the **extra-enterprise** agents, **enterprise-to-enterprise** agents and **material-resources-provision** (MRP) agents.

3.3 Simulation

Simulation can support decision-making process in two wais. First of them is a simulation of a new factory or of an overhauled or upgraded existing factory. The simulation tool supports a high-fidelity analysis of what the performance of the investment alternative will be. The second way to use a simulation tool is a decision support in factory control to test how changes in performance of key machines would affect the manufacturing process as a whole. ExPlanTech provides an integrated simulation environment that allows simulation of different manufacturing scenarios in order to make technology changes and control safer.

3.4 EE Access

It is possible to access the planning system remotely using the **thin client** or the **thick client** technology. The former approach requires merely an appropriate browser on client's side whilst the second one assumes installation of software based on Java and JADE technology on a user's computer but the latter provides user with more comfortable way to handle the planning system. The remote users exploit the functionality ranging from a passive observation of the system to active interventions (e.g. planning custom orders), which is determined by level of their access rights. Big stress is put on the security of extra-enterprise communication: public key cryptography in common with the secure JADE platform is employed to provide the maximal security level.

4. ExPlanTech Implemented

There are several industrial partners whom we have deployed the ExPlanTech solution with. They did not use all of them the identical collection of software system, while the solution for each of them has been custom tailored.

4.1 ExPlanTech in Modelarna Liaz

Modelarna Liaz spol. s r.o is middle size pattern shop enterprise in the Czech Republic. The customers of the enterprise are mainly from automotive industry from Czech Republic, Germany, Belgium and others. The patterns shop specializes on a single part production of pattern equipments, permanent moulds and dies, measuring and gauging devices, welding, cooling, positioning and machining fixtures and cubings (see an example of a production on Fig. 3).

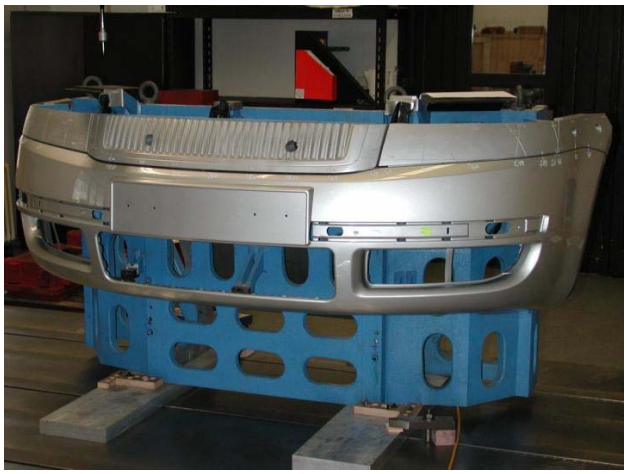

Fig.3. An example of Modelarna Liaz product

ExPlanTech was adapted on the planning level. The main goal was to improve middle-time and long-time horizon efficiency. The important criterion was the load of the strategic departments (machines) and delivery times. The multi-agent decomposition based planning within the ExPlanTech was implemented. The factory information system has been agentified and the Resource Agents are updated with real-time production feedback. One Planning Agent is responsible for whole planning course. On the other hand, several Cockpit Agents have been implemented for parallel connection to the system.

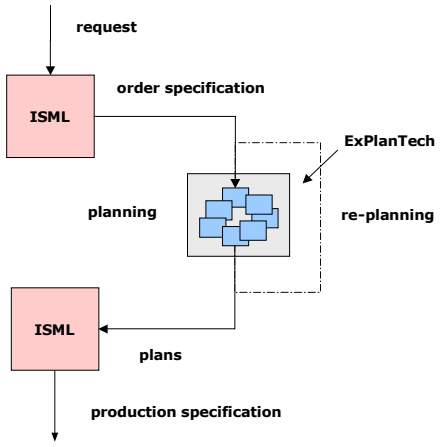

Fig.4. The role of ExPlanTech system in the production planning process at Modelarna Liaz

Upon the order specification in the company ERP system (denoted in Figure 4 as ISML) the ExPlanTech system produces a complete set of production plans that are again shipped to the ERP system. Planning a new order as much as a change in the factory shop-floor represented by the resource agents triggers a re-planning process of the all pre-committed plans within the ExPlanTech system.

Besides production planning the ExPlanTech technology supports the factory management with the extra-enterprise access to the planning data and automation of its supply chain management. The complete solution helps to find more efficient plans on the intra-enterprise level and improve the extra-enterprise activities. The faster and more precise cooperation with the suppliers and selling the free capacities can shorten the production lead-time and higher utilization of the factory. After several months of testing the system proved its potential by improving the machine utilization by 30% and due time reduction by 5.3%.

ExPlanTech in SkodaAUTO

The concept of the ExPlanTech technology has been successfully applied in design of the robust planning system for car engines manufacturing [9] in the new SkodaAUTO motor factory in collaboration of GEDAS, s.r.o and CertiCon, a.s. This is an example of a high volume production with few thousands of engines manufactured daily (see an example of an engine on Fig. 5). Given a high variability in types of motors to be manufacturing the planning problem is not a trivial task. The planning system was required to provide us with hourly plans for the period of six weeks. The production process (see Fig. 6) involves three production lines and three different part buffer stores.

Fig.5. An example of an engine produced at SkodaAUTO

The agent technology provided a great help in solving a highly complex problem of planning assembly line production. Planning has been designed to carry out on two independent levels:

– On a higher level a rough plan has been produced. This plan specifies an approximate amount of engines to be produced each day so that all the

requested constraints are met. We have used a linear programming based heavy-duty agent for elaborating this higher level plan.

– On a lower level the agents (each representing either a line or a buffer store) analyze the provided higher-level plan and check for conflicts. In an ideal situation the amount of conflicts is reasonable so that the agents can negotiate and solve the conflicts by swapping the tasks within days. The performance of this activity is given primarily by the higher level planning algorithm. Besides solving the conflicts, the lower level planning also provides ordering of tasks within a day.

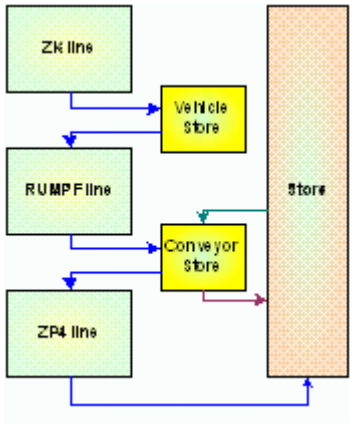

Fig.6. Motor manufacturing process at SkodaAUTO

ExPlanTech in BEHR

The use case of The BEHR GmbH & Co., an automotive supplier in the field of Cooling and Air conditioning systems, employs mainly the production simulation part of the ExPlanTech framework, supported by simplified planning and special Cockpit Agents and Meta-agents. The main purpose of the simulation is comparison of long-term effectiveness of several shop floor layouts. Simulation also allows finding of production bottlenecks, optimal position of product buffers and it can evaluate impacts of important machines failures. These results are very important in decision support during design of new or reconfiguration of an existing factory or even during an important control decisions.

From the implementation point of view, there are two main tasks for the ExPlanTech system:

– For a given shop floor configuration and for a given set of task find a possible sub-optimal production plan. The main goal is to produce tasks on time while keeping the resources utilization balanced. The planning

algorithm re-plans the production using spare resources in case of machine failure or overload.

– To simulate a production of particular plans with respect to production time deviations, probability of production of defect products, machines failure rates, human operators accessibility etc. While the planning agent uses one common production model with average production times, the simulation agents can contain particular detailed model of the machine containing many possibilities and events.

The planning and simulation components of ExPlanTech closely cooperate during the simulation. The simulation agents read processes the plans and try to execute them. The planning agent processes the results from the production process and continuously updates the plans so that they comply with an actual situation.

To obtain a meaningful simulation results, it is crucial to set a parameters of production models precisely. If the parameters with some systematical error are used, simulation results cannot fit a real production. In general, the most important are results of simulation of rare and critical situations. Unfortunately, the parameters necessary to emulate such situations are usually very difficult to measure.

ExPlanTech in CHATZOPOULOS

Hatzopoulos S.A. GR is one of the biggest company in Greece in its sector , and it is also one of the 5 largest companies at European level, having a market share of more than 26%. Its clients include amongst others: Chipita, Unilever, Procter & Gamble, PepsiCo Greece, PepsiCo Hungary, PepsiCo Cyprus, Nestle Greece, Nestle Bulgaria, Bic, Warner Lambert, etc. Big multinational clients of CHATZOPOULOS have repeatedly evaluated the company and included it in their accredited suppliers' shortlists.

Within the IST EC take-up action technology transfer project the ExPlanTech technology has been evaluated at the CHATZOPOULOS production site (in close collaboration with CertiCon and UniSoft S.A.). The production planning capacity of ExPlanTech has been exploited primarily for optimization of the production load at two different factory sites. For any new incoming order ExPlanTech provides the user with an estimate of the promised delivery date, taking into account the production place (whether it will be Plant #1 or #2 that will be responsible for the production), and allocating the required time for the construction of the required cylinders or the cliches (which are subject to the particular production "route" to be decided i.e. plant #1 or #2).

5. Conclusion

This contribution has illustrated the potential of the agent-based decision support technology in various fields of manufacturing – planning, supply chain management, simulation, extra-enterprise access, etc. The integration exercise that we have carried out at different industries validated that the agent based technology is viable in

situations where the planning problem is dynamically changing – e.g. project driven production, and needs frequent and continuous re-planning. In these situations the collective aspects of the agent technology have been exploited. At the same time we have identified a great potential of the technology in situations where the planning problem is inherently complex but it features some of the internal logic. This has been case of the high volume production, where not only collective aspects of agent technology have been used but also the integrative capabilities of agents have been exploited (e.g. integration of the linear programming heavy-duty solver). Obviously in situations where the planning data are widely distributed and not fully available the agent technology provided an elegant integrative and distributed planning framework. This was the case of the supply chain management and virtual enterprises integration. It has been shown that the multi-agent approach provides a specific modeling and simulation alternative to the known mathematical and system science modeling technologies for simulating the manufacturing process.

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