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Multi-agent system "Smart Factory" for real-time workshop management in aircraft jet engines production

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Abstract: The paper presents design principles of multi-agent system "Smart Factory" for real time resource management in manufacturing workshops. This objective is achieved by flexible event-driven reaction on changes in factory environment, resource allocation, scheduling, optimization and controlling in real time. The developed method of adaptive resource scheduling based on multi-agent technology, main functionality and architecture of the system are discussed. The results of application and measured benefits for aircraft jet engines manufacturer are presented.

Keywords: intelligent system, manufacturing, workshop, resource management, multi-agent technology, operation planning, real time.

1. INTRODUCTION

Multi-agent system "Smart Factory" is designed to increase factory productivity and efficiency by automated adaptive scheduling, forecasting and controlling of the manufacturing tasks in machine assembling workshops in real time. Adaptability means here that each event in the workshop, which takes place in reality and can influence the manufacturing plan, can be processed in "Smart Factory", reallocating previously scheduled orders and resources and resolving time conflicts. Examples of the events that can lead to rescheduling activities are: new order is coming, equipment failure, changes in priorities, emerging of new urgent tasks, delay in materials, etc.

The system can be applied for machine-production factories, which can be characterized by on-going innovations, complexity and dynamics of hand-made operations, as well as high uncertainty in supply and demand that require high level of real time adaptability in reaction on unpredictable events. It is also useful for capturing specific domain knowledge on manufacturing processes, products and materials, equipment and workers, and to provide the individual approach to each order or resource, to handle frequent changes of product/technology settings and to produce small series of different products.

In the paper the developed method of adaptive scheduling of workshop resources will be presented based on multi-agent technology as well as multi-agent system functionality, architecture and user interface. Accordingly with modern vision multi-agent system consists of autonomous agents (software objects) able to react on events and analyze situation, make decisions and communicate with other agents (Pěchouček, M., Mařík, V. (2008), Leitao, P., Vrba, P. (2011), Novas, J. M., Bahtiar, R., Van Belle, J., Valckenaers, P. (2012)).

Comparing with object-oriented approach the agent can't be invoked as a state-less object and implemented as a method; but can be asked to implement the task – for this reason he need to talk with other agents and make re-commitments; and this process can results in chains of re-commitments for finding new acceptable or/and near to optimum solution of complex problem. The decision of any complex task in this system is made evolutionary by interaction of dozen and hundreds thousands of agents which compete and cooperate with each other, create and break solution until the required quality level of problem solution is reached.

This paper is organized in a following way: first part will present domain-specific requirements for aircraft jet engines manufacturing; second part will give brief overview of existing systems in the domain and describe developed adaptive method of workshop resources scheduling; third part will present functionality and architecture of the system, user interface; fourth part will describe implementation results and value for aircraft jet engines manufacturer; finally some recommendations for next steps are given.

As a result it will be shown that multi-agent technology allows to solve complex problems in a real time which cannot be solved by other methods or tools, particularly, in the area of resource allocation, planning, optimization and controlling in real time for extremely complex domains of manufacturing (Skobelev, P. (2011).

2. PROBLEMS OF AIRCRAFT JET ENGINES MANUFACTURING

The "KUZNETSOV" corporation is one of the largest Russian national aircraft jet engines manufacturers which may include more than 50 thousands parts.

It has more than 40 workshops and about 4 000 workers, who is able to produce aircraft engines parts, assemble products and test them in real environment and also make repairments. The enterprise generates more than 1000 orders per day per one workshop, has more than 1000 suppliers, more than 150 workers in one workshop, etc.

Extreme complexity for modern aircraft jet engines manufacturers is caused by:

- Complexity of products and technology, variety of product parts.
- On-going innovations and fast changes of products, technologies, equipment, toolsets, etc;
- Large number and size of production workshops
- Many unpredictable events (demand and resource fluctuations, new orders, resource unavailable, etc.);
- Real-time resource allocation, scheduling, optimization and control requires shrinking time windows and individual strategies for different orders;
- Interdependent schedules of many workshops (mechanic workshop, assembling workshop, etc.);
- Intensive use of sensors and robotic multi-functional units which make enterprises more flexible;
- Numerous constraints on products, operations, workers skills, equipment, materials, compatibility, etc.;
- Individual agreements with major clients, suppliers, workers, etc.

And nowadays also aircraft manufacturers suffer from a lack of agility to respond to late requests for changes by customers. In practice it means significant delays until a response from engineering or supplier site takes part. This proves that operational scheduling needs to be handled in a more adaptive and flexible way.

The other requirements of modern manufacturing include support of scalability, integrated control of factory assets, factory and workshop level production automation and control, resource and cost effective aggregation of information across legacy systems (ERP, MES, SCADA, DCS), flexible and fast decision making support, support of service-oriented model of factory, integration with sensor networks.

3. STATE OF THE ART

Resource scheduling is one of the NP-hard complex problems in modern manufacturing (Leung (2004), Vos (2001)).

In spite of significant progress regarding development of large-scale Enterprise Resource Planning (ERP) systems and batch scheduling systems, opportunities of the enterprises on development of real time scheduling systems remain very limited. Traditionally the ERP systems and schedulers offered by such well-known companies, as SAP, Oracle, Manugistic, i2, ILOG and others implement different versions of linear or dynamic programming, constraint programming and other methods, based on combinatory search of options in depth, for example, a method of branches and borders. To reduce the number of options in combinatorial search new methods consider heuristics and meta-heuristics, allowing to provide good decisions for reasonable time and reducing search iterations ("greedy" local search methods, simulated annealing, tabu search ant optimization, adaptive memory programming, etc). But even in this case it is difficult to take in consideration algorithmic preferences and constraints, search is very time consuming and results are just not feasible.

At last period of time a number of new products arrived which have some features for real time scheduling: ORTEMS, Alfa, Infor, QuintiQ and some others. All these systems provide the abilities for job scheduling, managing technological processes for production, production planning and monitoring of orders execution but there is no support for event-driven scheduling.

As a result classic methods of resource optimization have a number of very important limitations:

- Do not consider complexities of the modern business operating in thousand of orders and resources, supporting interdependency between all operations, reflecting and balancing interests of many parties involved;
- Do not provide opportunities for adaptive planning in real time which requires dynamic event-driven conflict solving in already available schedule;
- It's supposed that all orders and resources are "identical" and given in advance but in practice they all have their own individual criteria, preferences and restrictions, ehich can change during the system work (service level, time of delivery, costs and profits, risks of delivery, inconvenience of the driver, etc);
- Do not give the tools for the aquiring knowledge which are specific to every enterprise, influencing quality of provided schedules;
- Do not allow a dispatcher to explain and adjust decisions easily and in interactive way.

All this constraints not only reduce productivity and efficiency of existing methods and tools, but also in practice in many respects stops their use.

As a response to address on these challenges a number of R&D prototypes was developed with the use of multi-agent technology. Most interesting solutions include Production 2000+ for automation of production line for producing cylinder heads for four-cylinder diesel engines at the Daimler Chystler factory plant in Stuttgart, Germany, MASCADA for a section f the painting center at the Daimler-Benz AG passenger car plant in Sindelfingen, Germany, Rockwell Automation applications for steel rod bar mill of the BHP Billiton in Melbourne, Australia and for chiller water system, heating, ventilation and air conditioning of US Navy ship (Leitao, P., Vrba, P. (2011)). Another advanced solutions are system implemented in SkodaAuto by Gedas, s.r.o., Czech Technical University (CTU) in Prague and CertiCon and ExPlanTech developed in Gerstner Laboratory, CTU. The latter was deployed in Moderlana Liaz in cooperation with CertiCon. (Pěchouček, M., Mařík, V. (2008)).

This first experience is showing the applicability of multi-agent technology but also that the multi-agent solutions for manufacturing are very dependable from problem statement and specifics of enterprises.

4. THE METHOD OF ADAPTIVE SHEDULING BASED ON MULTI-AGENT TECHNOLOGY

Unlike traditional enterprise resource planning systems operating mainly in batch mode with daily-weekly-monthly cycles of scheduling, the proposed system is event-driven and works continuously on server in real time, adaptively and individually rescheduling the selected orders and resources that are affected by events (Skobelev (2011)).

The developed adaptive method of real time scheduling is based on multi-agent technology with the use of a manufacturing ontology, which includes typical classes of equipment, specifications of product structure and technological processes (sets of linked operations), workers skills, etc., which complies with ISA 95 standard. In this approach software agents represent interests of orders, resources, workers, machines, operations and materials, using relationship between the operations.

The system provides a fast adaptive respond to new events coming and also proactively improves operation plan by the use of free machine time or worker slots, by the sequence of shifts and reallocations of previously scheduled operations to other resources. In this case even each "small" event can trigger unexpectedly big changes in schedules which are considered as "unstable equilibriums" (since the system never stops) being propagated via the whole schedule of workshop by the chain of changes. However, in practice this "wave of changes" is limited by bonuses and penalties of virtual market of agents and it is quieting after a few steps.

As a result, the work plan of the workshop is built not as just an output file of data produced by a classical combinatorial search, but as a network of agents of orders, products and operations and resources, which is very close to PROSA architecture (Novas, J. M., Bahtiar, R., Van Belle, J., Valckenaers, P. (2012)) and represents the balance of interests of all involved parties, which is achieved by the negotiations of agents. During these negotiations, the system takes into consideration the current state of plans, importance of orders, structure of products, technological processes, specifics of workers and equipment, materials and instruments availability, sequences and time of operations.

If needed, the dispatcher of workshop can intervene this active plan interactively at any time and provide smart manual rework of the schedule by drag & drop of operations – and the plan will be automatically revised and rescheduled.

The results of the scheduling are presented for workers on touch-screen terminals that support interactive communication with managers, engineers and workers.

All these features provide opportunity to reduce complexity of scheduling significantly and make it faster, more adequate, accurate and reliable.

Users can simulate the new orders coming and check how it can be placed in the current production plan and how these orders can affect other orders, for example, shifting or even pushing out the previously allocated less important orders.

Let us consider an example of interaction in the case of receiving a new operation.

A resource receives a new task to execute having three existing operations in his schedule. Operation 4 discovers the conflict with Operation 2. Operation 4 tries to move to the left and use all free time to avoid a conflict (Fig.1).

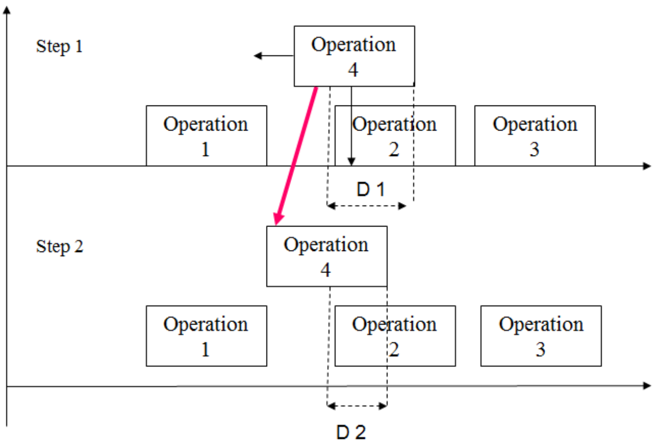

Fig. 1. The first step of agent interaction

Operation 4 determines the intersection slot with Operation 2 (D2). Operation 2 agrees to move to the right, but faces the constraints of Operation 3, which cannot move to the right (Fig. 2).

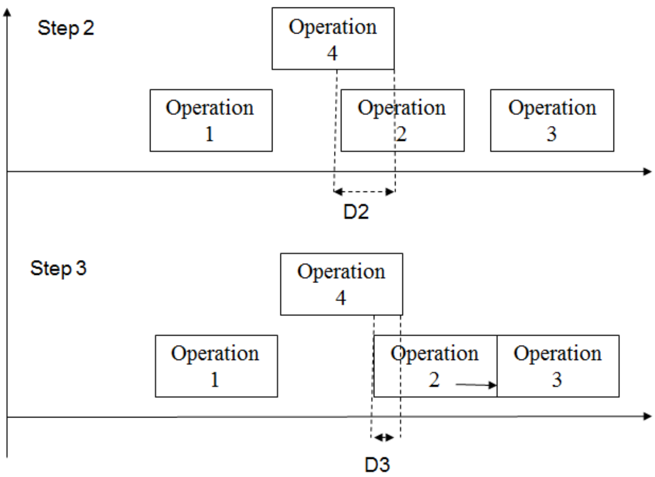

Fig. 2. The second step of agent interaction

The negations wave comes from Operation 3 to Operation 1. Operation 1 agrees to move by D3 to the left. The conflict is resolved and Operation 4 is successfully allocated to the resource (Fig.3).

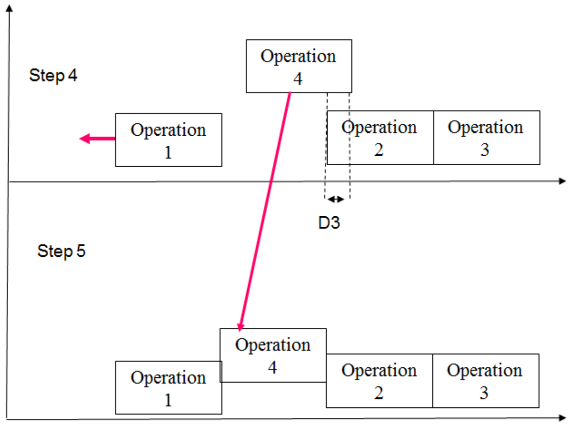

Fig. 3. The third step of agent interaction

5. ARCHITECTURE

The system architecture and key components are represented by 3 main tiers including Server and Client Components and Data Base (Fig. 4).

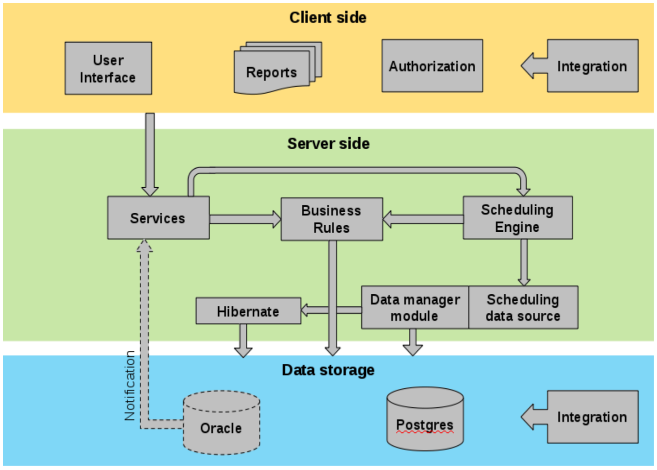

Fig. 4. The Architecture of System

Adaptive scheduling engine includes a manager of scheduling which is responsible for events processing, data loading, starting the world of agents. The core part of scheduling engine includes agent dispatcher, messaging services, agent life cycle support, creation and termination of agents, communication protocols between agents and scene support representing the resulting schedule (Tyrin, I., Vylegzhanin, A., Skobelev, P., Kuznetsov, O., Kolbova, E., Shepilov, Y., Kozhevnikov, S. (2012), Goryachev, A., Kozhevnikov, S., Kolbova, E., Kuznetsov, O., Simonova, E., Skobelev, P., Tsarev, A., Shepilov, Ya. (2012)). For the event processing, there is no difference between different events: they are processed on the first-in basis regardless the consequences and their amount.

The list of the developed key agent classes is presented on Tab. 1 and the main lines of negotiations among agents are presented in Fig. 5.

The schedule of the workshop represents so called “scene” (formal representation of model of situation) which works as a“mirror” of the reality. This scene is formed as a semantic network of key objects and relations of the manufacturing ontology linking orders and operations, operations and workers, competencies, etc. These links are continuously investigating by agents and help them to narrow combinatorial search and find reasonable options by analysing the “topology” of the schedule.

Table 1. Main classes of agents

Agent name	Agent description	Attributes
Order	Order looks for best possible allocation	Cost, Priority, Deadline, Details
Organization	Tries to achieve and improve given KPIs, observes situation and change strategy, constraints and preferences for harmonizing parties involved.	Upper organization, Organization type, Chief, Expected results
Worker	Wants to be busy all the working time and get bonuses for quality, performance, etc. And improve his working skills to get higher level of qualification	Organization, Schedule, Features, Professions, Known machine models, Performance, Salary
Machine	Wants to be loaded as much as possible, but not to exhaust its resource	Organization, Machine model, Energy consumption
Technological process	Coordinate technical operations to be properly scheduled	Deadline, Inner operations, Material, Detail dimensions
Technological operation	Searches for best possible workers and machines, have start/stop preferences	Profession, Rank, Machine model, Duration, Preferred start/stop
Operations lot	Tries to consolidate operations to improve efficiency	Inner operations
Other agents	Materials, Instruments, Transporter, etc.	

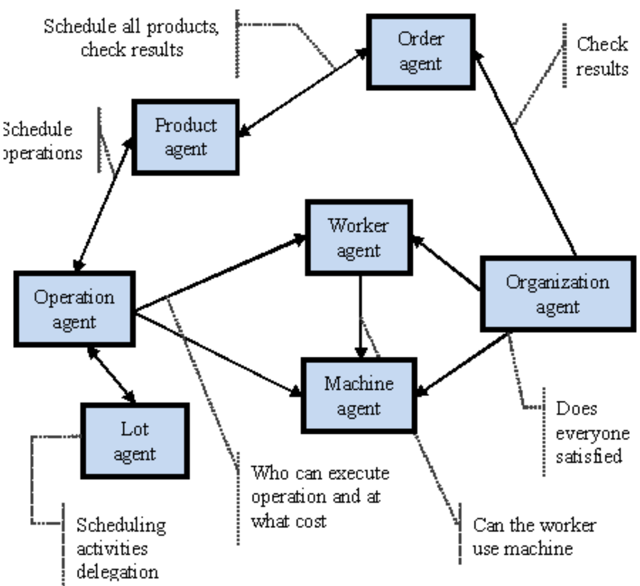

Fig. 5. Main lines of agent protocols of communications

The schedule is ready when the system has reached the required threshold or no agent is able to improve its state or time for getting results is expired. The threshold means the threshold of agents' satisfaction and is defined by the user settings. The settings correspond to the priorities for the planned order/product (e.g. lateness is less than 20%, just in time scheduling mode, etc.)

The system also can be integrated with existing programs, such as warehouses, payroll workers, accounting systems, etc. There is a specific standard of the required format and data that are necessary for the system operation, which can be transferred in batch mode using XML or by integration at the database level using triggers.

6. USER INTERFACE

The key screens of the system are presented in Fig. 6-11.

As it is shown in Fig. 6 all orders for workshops are displayed with the current order status and with different filters for sorting orders. Statuses of orders: not started, planned, started, executed, in the preparation process, stopped, delayed, postponed, etc.

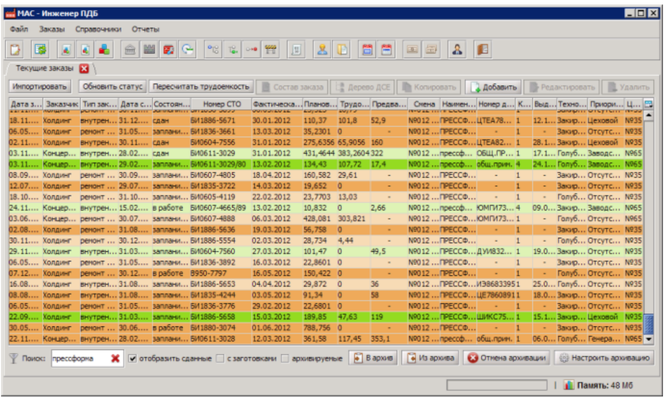

Fig. 6. Statuses of Orders

Fig. 7 is showing how the structure and assembling technology for manufactured product can be loaded to the system from PDM system.

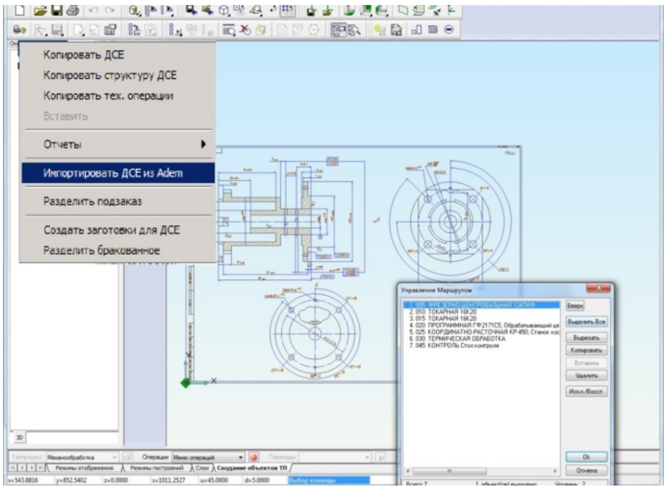

Fig. 7. Loading Design of Product for Order

Event Queue gives a possibility to managers to enter information of new events and start rescheduling as it is shown in Fig. 8, for instance, entering a new order for manufacturing loaded product (hierarchy components of which are visualized on the left).

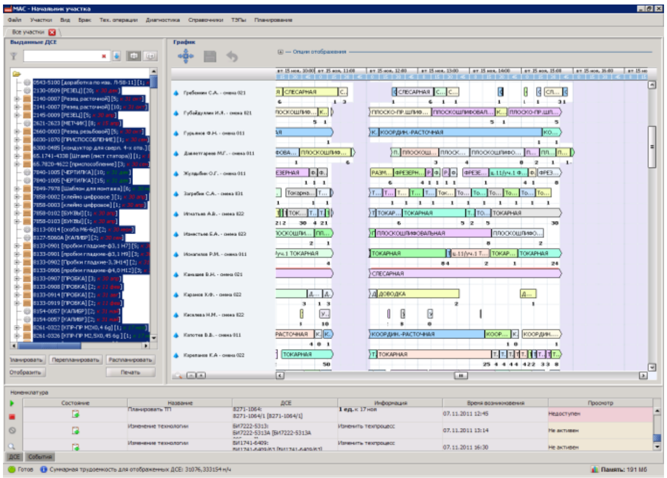

Fig.8. Queue of Events and Schedule of Workers

In Fig. 9 combined Gantt and Pert diagrams are presented which show the interdependencies between the manufacturing operations. The user can select any operation here and "drag and drop" it to another worker as well as merge or split operations and adjust plan by this event triggering an automatic chain of changes in the schedule accordingly.

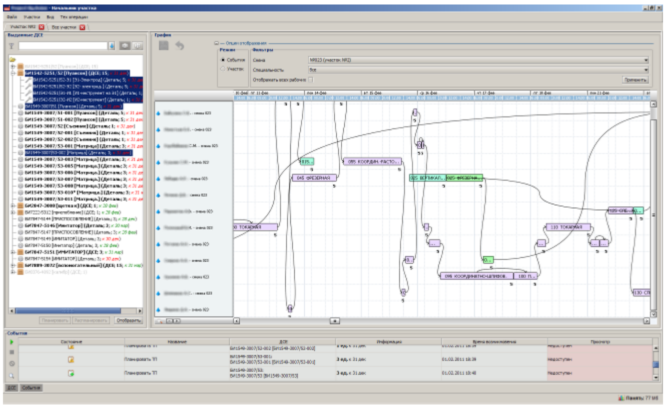

Fig. 9. Interactive adjustment of workshop schedule

In case worker has not enough skills for the operation or it may cause delays and other problems, the system will highlight this operation in red color and give a warning message to the user (Fig. 10).

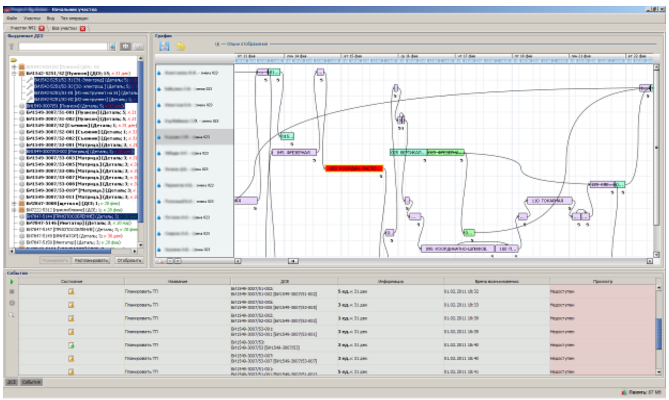

Fig. 10. Agent of operation signals about mismatch with worker skills

List of tasks for workers can be generated and printed in traditional form (Fig. 11) or presented on kiosk with touch screen for direct interactions with workers.

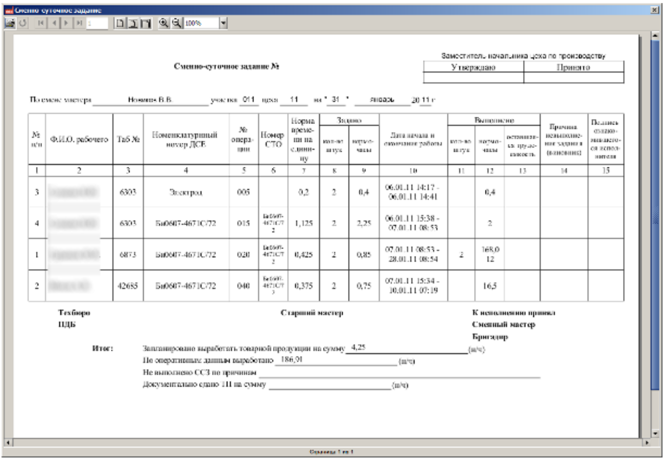

Fig. 11. List of automatically rescheduled daily tasks for the selected worker

7. IMPLEMENTATION RESULTS

The implementation of “Smart Factory” solution for JSC “KUZNETSOV” is still in progress but first experience of system application shows a high potential of the adaptive scheduling for increasing the efficiency of manufacturing.

The following results are expected as the outcome of the first application tests:

- increase of the workshop productivity - by 10-15%;
- reduction of the efforts on tasks allocation, scheduling, coordination and monitoring for running project - by 3-4 times;
- increase of the efficiency of resources - from 15% and more;
- reduction of the time of response to unexpected events - by 2-3 times;
- increase of the percentage of the enterprise orders completed within the timeframe - by 15-30%.

The more detailed results will be measured and reported after delivery and time period which is required to become familiar with the system – as it was measured for electronic device manufacturer Axion Holding (Tyrin, I., Vylegzhanin, A., Skobelev, P., Kuznetsov, O., Kolbova, E., Shepilov, Y., Kozhevnikov, S. (2012)).

8. NEXT STEPS

The main prospects of the further system development are associated with the implementation of the network-centric p2p platform for coordination of the work of departments, the development of the adaptive scheduling method of multi-criteria decision making with self-regulation by criteria, with the use of the cloud computing to provide the developed system by SaaS model.

The key ideas presented above are will be developed in IP project “Adaptive Ramp-Up Management (ARUM)” of FP7 program “Smart Factory” under Airbus / EADS coordination in cooperation with Universities of Prague, Cologne, Manchester, Braganca and some other partners (more info is here - www.arum-project.eu).

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