Agent-based Supply Web Coordination - A Computer Manufacturing Case

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Abstract:
In the framework of our research project, the entities of a supply web are designed as software agents and are enabled to simulate autonomous decisions of production planning and logistics. Those are based on specifically designed protocols to coordinate the intra-organizational and inter-organizational trade of goods and services. The focus of this paper is the design of a mechanism that helps economic agents - either autonomously or cooperatively planning - to achieve Pareto-optimal allocation of resources via a completely decentralized coordination of a logistics network. By performing simulations with the implemented protocol using a scenario from the computer industry as a benchmark, we show the feasibility and efficiency of the designed mechanism. The approach enables each agent to exploit the external effects caused by resource constraints of its supply chain contractors by adapting its production planning. Additionally, the system's capability to reconfigure itself in case of production resource failure is increased.

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1. INTRODUCTION

Cooperation in supply chains is performed by autonomous organizational units, i.e. the entities / companies will only behave in a cooperative fashion as long as this is in their own interest. Compared to simple chains, cooperation has a higher level of complexity due to the fact that in supply webs, company's suppliers or customers may in turn have a subset of the company's suppliers or customers as their own suppliers or customers, i.e. have direct links to them. Furthermore, supply webs may overlap, i.e. the same company participates in different supply webs, causing partners in one supply web to act as competitors in another (so-called coopetition [Buxmann/König 00], [Brandenburger/Nalebuff 96], [Kjenstad 98]). The need for a distributed Supply Chain (or Web) Management (SCM) occurs [Grolik et al. 01], [Kjenstad 98] in these cases.

Distributed SCM requires highly integrated information processing in the entire supply web. Although not all internal information available is provided in the supply web, fast information logistics of distributed information gets crucial for automating supply web planning and control. At best unforeseen events (like break-down of a machine or acquisition of a new order) should be propagated to all partners with zero-latency to allow an immediate distributed realignment of their plans according to their individual goals.

Although bargaining and contracting interactions play a major role for all actors of supply webs, the area of standardized bargaining protocols is still a research field with many open questions [Pete 00]. In this context we are focusing on protocols for renegotiating based on propagated multi-time-point supply and demand prices. Compared to the standard delivery contract referring to a single point in time (or a time window) and a penalty, when this is not met, the multi-time-point functions allow for a direct specification of opportunity costs of late or early delivery. In our research project, we use a multi-agent system to calculate these functions coupled with automatically recontracting.

The following chapter provides an overview of the research on the topic of supply chain optimization based on multi-agent systems.

2. SUPPLY CHAIN MANAGEMENT BASED ON MULTI-AGENT SYSTEMS

Software agents are associated with the properties autonomy, rationality, proactivity and interactivity[1] [Wooldridge/Jennings 95], [Franklin/Graesser 96]. Autonomy characterizes the ability of the agent to act on its own behalf [Castelfranchi 95], rationality is attributed to the desire to maximize its utility [Newell 82], while interactivity is linked to the use of communication languages like KQML [Finin, et al. 94] or FIPA-ACL [FIPA 97]. Both languages are based on the speech act theory [Austin 62] [Searle 69] and coordination protocols (e.g. [Davis/Smith 83], [Haugeneder/Steiner 91], [Burmeister et al. 93] [Barbuceanu/Fox 95a]). These properties are necessary for agents to act as (widely) autonomous, loosely coupled, self-coordinating entities in an open multi-agent system. The use of game theory is driven by the assumption of rationality combined with uncooperativeness amongst the agents [Zlotkin/Rosenschein 94] and leads to the application of the CONTRACT NET protocol [Saad 96], [Sandholm/Lesser 96], [Sandholm/Lesser 01] and different types of auctions [Vickrey 61], [Varian 95], [Weinhardt 96a], [Walsh et al. 98], [Ruß/Vierke 99]. Properties of agents like intelligence[2], proactivity and interactivity are based on knowledge representation in combination with cognitive abilities [Van de Velde 95] and / or mental states [Shoham 93], [Rao, Georgeff 91], [Singh 94], [Cohen/Levesque 95].

In the multi agent systems (MAS) domain, numerous approaches of research focus on production planning and control (see e.g. [Zelewski 95], [Kassel 96], [Corsten/Gössinger 97]) or transportation planning (see e.g. [Fischer et al. 93], [Falk et al. 93], [Gerber et al. 99], [Fischer et al. 98], [Ruß/Vierke 99]). Knowledge-based MAS are successfully deployed in several production and logistics oriented applications. [Kwok/Norrie 93], [Pan et al. 89], [Roboam et al. 91], [Sadeh 94], [Smith 89]. In the following, a variety of different approaches that take the complete supply chain into account are summarized.

Fox and Barbuceanu of the University of Toronto deal with tactical and operational coordination problems of the supply chain (cp. e.g. [Fox et al. 93], [Barbuceanu/Fox 95], [Barbuceanu/Fox 97]. A similar approach is applied by Swaminathan et al. [Swaminathan et al. 98], which provides a flexible

[1] A common accepted definition of the term software agent doesn't exist. Nevertheless

and reusable modeling and simulation framework utilizing agent-based structure and control elements from the decision support systems domain.

In MASCOT (Multi-Agent Supply Chain COordination Tool) [Sadeh-Koniecpol et al. 99], [Kjenstad 98] hierarchical organized agents support planning and scheduling decisions concerning the entire value chain. MetaMorph II [Shen/Norrie 98a], [Shen/Norrie 98b] is based on a hybrid architecture in which agent subsystems are linked with each other through mediators; the agents cooperate by using the Contract-Net protocol [Smith 80].

ANTS (Agents, Networks, Trees, and Subgraphs) architecture [Sauter/Parunak 99], realized with large populations of simple agents, use a least commitment scheduling approach based on the Contract-Net, which defers decisions on process sequences until the ultimate possible moment. In this context agents optimize by rescheduling based on probabilistic committed capacity resources profiles over time.

In the AARIA (Autonomous Agents for Rock Island Arsenal) project [Parunak et al. 98a], [Baker et al. 99] resource agents control virtual production efficiently and effectively by successive job dispatching. The DASCh (Dynamical Analysis of Supply Chains) project [Parunak 99], [Parunak 98b], [Parunak et al. 98b] applies these approaches to industrial supply networks and explores the effects of their dynamical behavior.

Zeng and Sycara [Zeng/Sycara 98] develop a model of inter-organizational electronic commerce that explores various new choices and opportunities offered in the electronic marketplace. Their research focuses on coordination of just-in-time delivery in a flexible and cost-effective manner. [Strader et al. 98], [Lin et al. 96], [Lin 96] employ this approach in their Swarm multi-agent simulation platform too.

In the MAGNET system (Multi-Agent Negotiation Testbed) [Collins et al. 00a], [Collins et al. 00b], [Collins et al. 99] supply and demand agents negotiate with each other through a market-based infrastructure using a so called "finite-leveled-commitment". The market acts as an explicit intermediary in this context.

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[2] Intelligence is understood as being funded through existing cognitive capabilities and not as „emergent“.

In addition, some researchers proposed the appliance of mobile agent technology for enterprise integration and supply chain management [Brugali et al. 98], [Papaioannou/Edwards 98], [Papaioannou/Edwards 00], [Szirbik et al. 00], [Szirbik et al. 99].

In contrast to these approaches, we focus on the topic of distributed scheduling without providing process information to the supply web partners. Section 3 specifies the developed protocols and mechanisms. Questions related to the migration of planning agents will be the focus of our forthcoming research, and will therefore not be discussed in this paper.

3. ARCHITECTURE AND PROTOCOLS FOR A DISPOSITIVE SUPPLY WEB COORDINATION

In the framework of our research project the entities of the supply web are designed as software agents. These agents are enabled to simulate autonomous dispositive decisions of production planning and logistics. Those are based on specifically designed protocols to coordinate the intra-organizational and inter-organizational trade of goods and services. In principle we assume that all interacting agents are *truth-telling*, i.e., the agents don't pursue the strategy to maximize their profit by willful misinforming other agents.

Each agent holds information (agreed delivery time and prices) which is comprised in the current contracts. Additionally, they exchange indirect information about their current planning situation by the exchange of time-price-functions, i.e. prices of demanded and supplied goods for several delivery times. Therefore, the agents have restricted knowledge about third party information, e.g., planned processing time, idle time of resources and contracts between other agents. As far as we know, efforts based on a relaxation of the traditional concept were not subject of research up to now. This might be due to prohibitive costs of complex negotiations in established systems.

3.1 Usecase

The usecase examined in this paper is part of the supply web of the computer manufacturer Tokop Corp. (cp. figure 1). The arrows in the picture symbolize skeleton contracts between the enterprises inside the supply web. In our artificial scenario, the Tokop Corp. is producing six different series, which are sold to the retailer Gooddeal. For the production of the three series, Tokop Corp. needs special computerboxes which are supplied by the Xelox Corp.. For the production of the other three series, three different computerboxes supplied by the Compu Corp. are needed. For the manufacturing of the computerboxes, specific CD ROM drives are needed for each series, supplied by the Bighit Corp. For the production of the CD ROM drives, the Bighit Corp. recieves series specific digital analog converters from Transtec Corp. and Bellatino Corp.

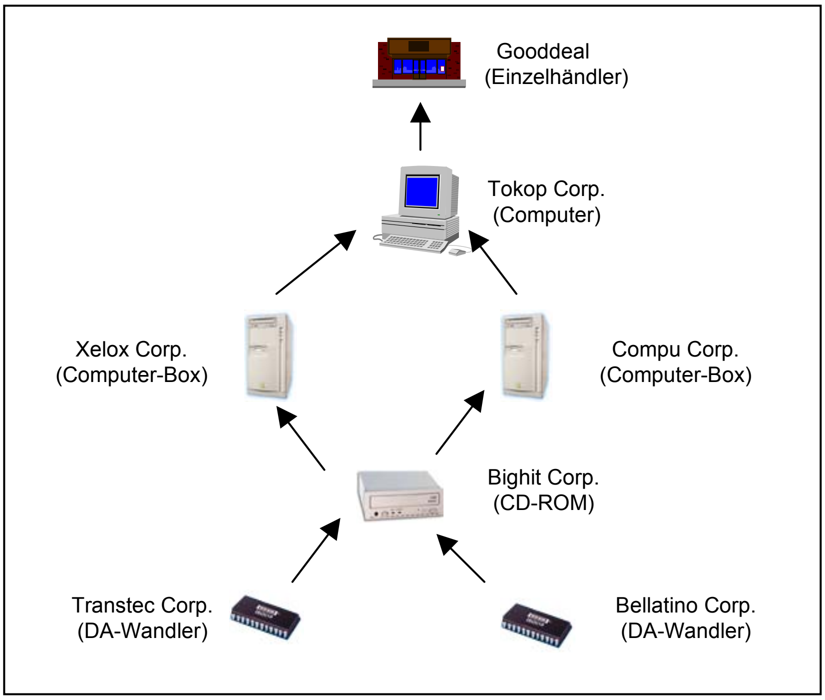

Fig. 1 Part of the exemplary supply web of the computer branch

In the following, we will construct a planning situation in the supply web. The Tokop Corp. has scheduled one job for each of the six series and has committed to provide the jobs to the retailer Gooddeal, whose utility is determined by the arrival of the latest delivery. Every manufacturer of the supply web has contracted the delivery of his product with his successor with regard to the respective job. Each contract is defined by a pair of delivery time and price agreed upon by both parties.

Figure 2 shows the respective schedules of the production agents of the supply web. Each of the six jobs (identified through uniform pattern) is processed by each production agent using machines capable of only one task at-a-time, whereby the processing of each job by an agent is only possible after the termination of the predecessor. The processing of each task must be uninterruptible. In addition, we neglect transportation times, transportation costs, and storage cost. The first number shown at the tasks represents the point in time when the product will be supplied by the predecessor, the second number representing the planned start time of task execution. The “no“ at the first task of a job indicates that there is no predecessor.

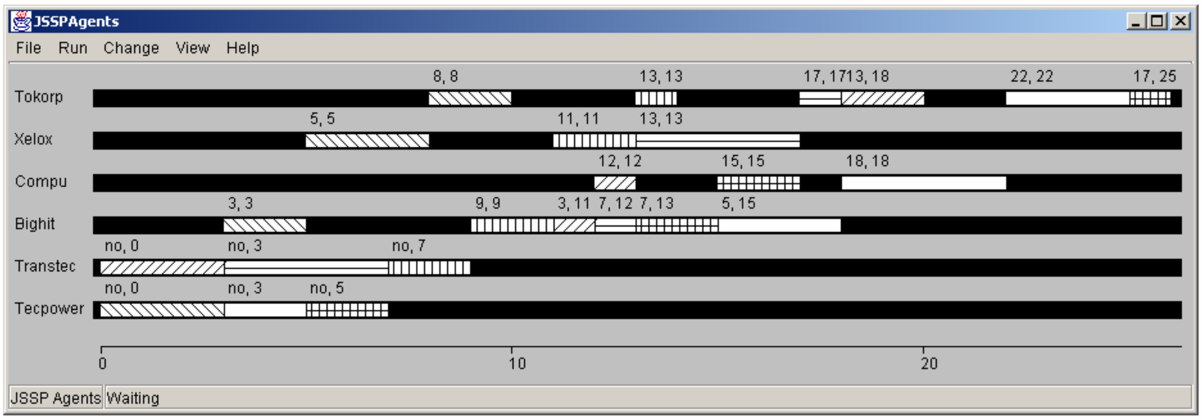

Fig. 2 Initial schedule with current contract times and planned production times in the supply web

The above assumptions correspond widely to the job shop scheduling problem (JSSP), well known in operations research. The main difference is the assumption about the allocation of information because, in the case of the JSSP, it is assumed that all information is available at a central position.

3.2 Propagation of price vectors

The agents not only possess information (agreed delivery time and prices) which is comprised in the placed contracts but also change price vectors for all relevant points in time the service might presumably be contracted for.

Compu Corp. and Tokop Corp. contracted a delivery (for the "checkered" job) at time 17. At the start of our simulation, all contracts are arbitrarily[3] fixed at a price of 1000 monetary units (MU). Relating to this contract, Compu Corp. now communicates a (time-based) price function to Tokop Corp., indicating its willingness to *charge* more or less than the agreed price for an earlier or later delivery. Since an earlier delivery is not possible, no values are communicated (i.e. the price is "infinitely high"). For a delayed delivery, Compu Corp. is not willing to offer a discount in this stage of the negotiation process, i.e. his prices are the same as for current contract time 17. All suppliers communicate their time-based price vectors to their customers while the customers communicate their respective willingness to *pay* more or less for early or late delivery in the analogue way. The upper diagram of figure 3 shows the resulting time-based offers (prices of the supplier of Tokop Corp. relating to the "checkered" job). The vertical line relates to the agreed delivery time specified in the corresponding contract.

[3] Because only an agent's relative profit or loss are relevant in the evaluation of any replanning activities, this assumption does not pose any restrictions to generality.

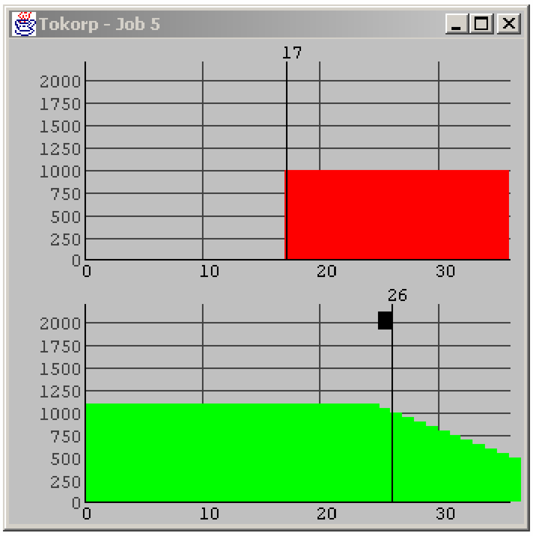

Fig. 3 Time-based supply and demand prices visible to Tokop Corp. (for the "checkered" job)

The lower part of figure 4 shows the demand side, communicated to Tokop Corp. by the retailer, being the terminal to all six jobs. The vertical line indicates the agreed delivery at time 26. Each time unit of delay will only be accepted by the retailer for a rebate of 100 MU. A speedup of one time unit, on the other hand, pays off by an increase of the customers' willingness to pay[4] to a total of 1100 MU.

Because we abstract from storage cost in this first model, all time-based price functions are monotonous, since no customer disagrees to an earlier delivery and no supplier to a later one.

For an earlier delivery an agent would only be willing to pay more if he receives (at least) the same amount from the successor for an earlier contract.

This means that each agent combines the time-based demand function received from his customer(s) with information concerning his current planning situation to derive his own time-based demand function that he communicates to his supplier(s). This way the demand price functions propagate from the end of the supply web (the retailer) to the beginning, while the time-based price functions for the supply propagate the opposite direction, i.e. from the manufacturer of the first raw materials to the retailer. Of course, the rationale that an agent uses to "blend" his own local information on rescheduling opportunities into this propagation process ultimately determines his profit (and the profit of other agents).

[4] The retailer agent's willingness to pay is exogenous to the model and thus will not change during the renegotiation process.

3.3 *Rescheduling*

For the processing of the initial schedule, i.e. the completion of the last task of the last job (job 6, checkered) through the Tokop Corp., 26 time units are needed. This is far above the minimal schedule that could be generated if (and only if) all information were available to a central planning agent.

3.2.1 Task rescheduling based on price functions

An agent not having access to any information, except for time and price information agreed upon in the current contracts with its customers and suppliers, tries to improve its schedule by randomly selecting new start times for its tasks and then requesting up-to-date price information from both predecessors and successors in the supply web. Whenever this step turns out to be profitable (compared to the status quo), both contracts get updated. In order to reduce communication efforts and the number of rejected and therefore wasted rescheduling steps, agents may proactively propagate price vectors for all relevant points in time the service might presumably be contracted for. The agents store the supply and demand prices for each point of time, which they get from the other supply web agents. During their planning, they have access to these stored prices at any time. Based on these prices, the optimal alternative schedule of the selected task is sought.

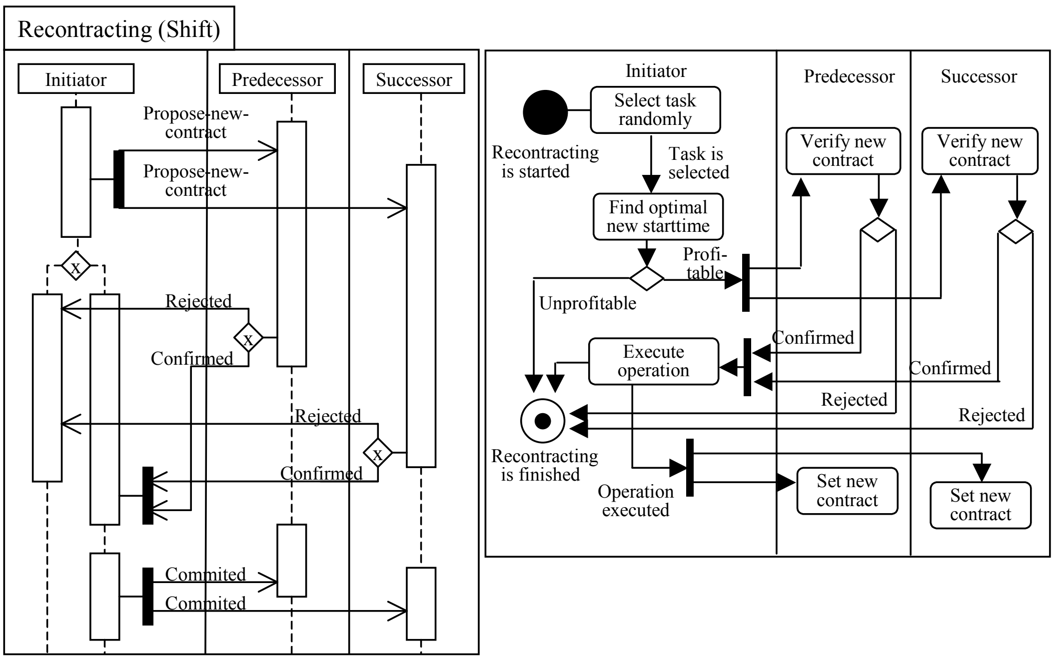

Fig. 4 Rescheduling based on price vector information (AUML[5])

5 For a better illustration of the process we choose the Agent Unified Modelling Language (AUML). To get further information we suggest reading the following papers [Odell et al. 01], [Bauer 99] or refer to the website http://www.auml.org.

Figure 4 illustrates the rescheduling activity: Since every agent may use the stored price vectors received from his supplier or customers to find a tentative answer to the question of whether the partner would agree to a specific rescheduling proposal, there is no need to communicate a proposal until a point in time has been found that also makes one's partners better off. However (due to the asynchronous planning of all partners in the supply web), the available "copy" of the partners' price vector might turn out to be outdated, whenever the actual rescheduling is proposed, thus making it necessary to reconfirm before the actual rescheduling occurs (which is done by simply transmitting a copy of the regarding contract time and price). Whenever it gets accepted, the requesting agent makes the final decision whether or not the old contract gets replaced by the new one. This allows for asynchronously requesting multiple binding offers and then substituting all relevant contracts in one single rescheduling step.

3.2.2 Simultaneous Rescheduling of two tasks by a single agent

As we pointed out above, propagating time-based price functions should help to reduce communication overhead for unprofitable offers. On the other hand, running a complete local optimization of the internal rescheduling opportunities, and then trying to implement this schedule by simultaneously renegotiating all contracts, did not yield acceptable results either.

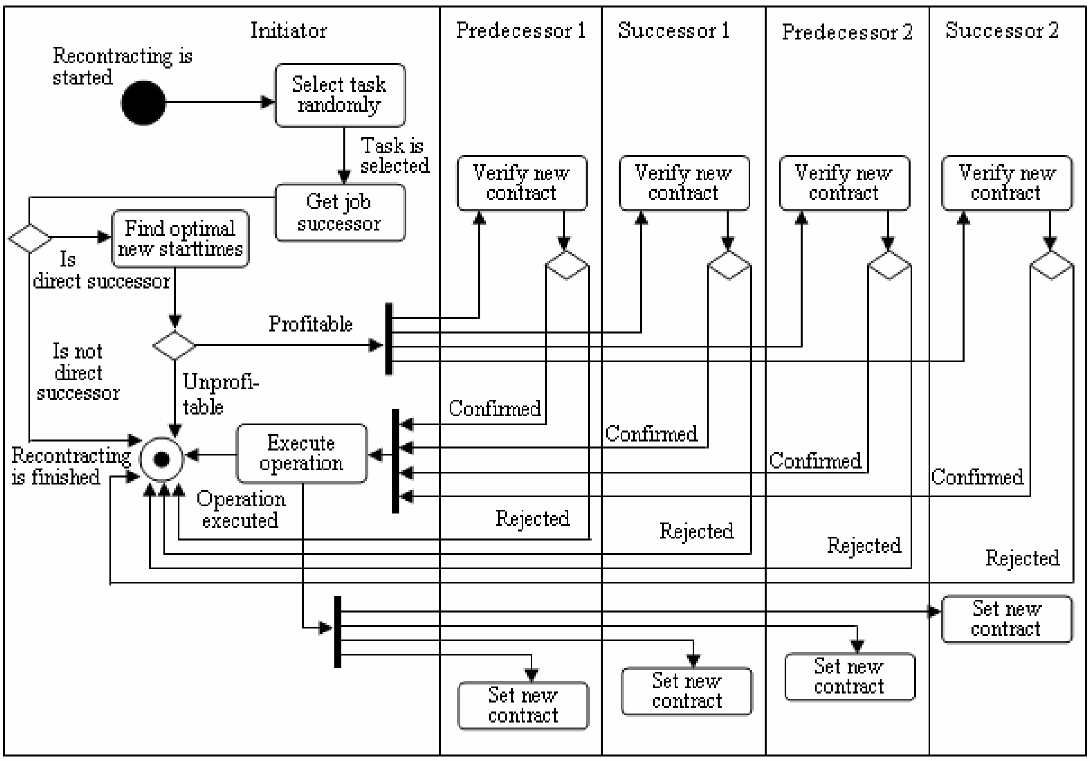

Fig. 5 Swap protocol

Therefore we implemented as a “compromise” the Shift&Swap protocol, that randomly (with a given probability) decides either to try shifting a single task (as outlined in figure 4) or, alternatively, to swap the order of two adjacent tasks (cp. figure 5).

Assume that Tokop Corp. randomly selects the white task (refer to figure 2) for an operation. Unfortunately, this task is completely stuck due to its successor and supply contract, leaving no room for any shift. Alternatively, the agent can try to swap the task, i.e. he tries to reverse the order of two tasks’ execution, and to schedule both to the earliest possible point of time considering his workload. The immediate internal successor task to the white is the checkered one, and the profitable effect of their swap may be derived from the current time-based price functions displayed in figure 7.

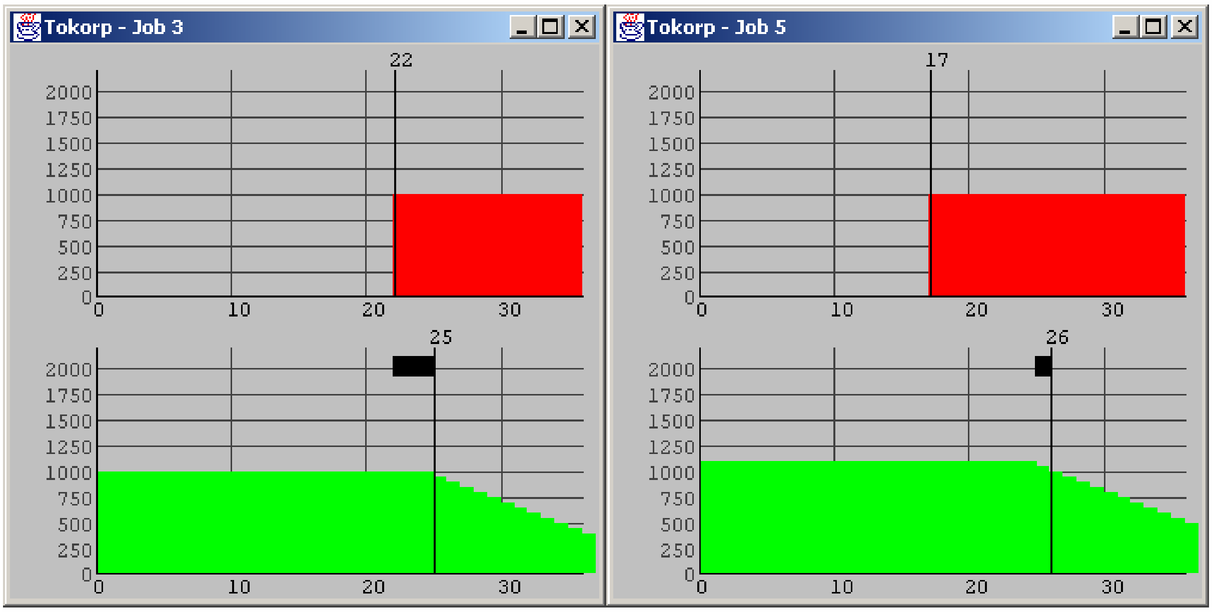

Fig. 6 Time-based supply and demand price functions communicated to Tokop Corp. for the white task (job 3, left) and the checkered task (job 5, right)

The checkered task (job 5) will now be terminated at time 21, yielding 1100 MU which is an excess profit of 100 MU. In this case the contract times do not change for the white task (job 3), and the retailer is still willing to pay the full 1000 MU, leaving Tokop Corp. with a total profit of 100 MU from this swap.

Note that for the checkered task Tokop Corp. receives his input by time 17, and thus there is no need to renegotiate with the supply side for this swap. The same is true for the white task. But in general, side effects for a maximum of four agents have to be considered to evaluate the profitability of a swap; two agents on the supply and two on the demand side. For a shift, there is only one agent involved on the demand side and one on the supply side. Of course, this number increases, once we introduce multiple sourcing.

4. WELFARE ANALYSIS FOR THE SUPPLY WEB

The optimal solution to the above introduced supply chain setting results in a completion time of 19 time units. To test our protocols we transformed the problem to a multi-agent system and initiated a feasible solution by randomly drawing tasks from the remaining set of tasks (which have no unscheduled predecessor) and let the agent responsible for the execution schedule it to the earliest possible start time. The (5000) initiated schedules have an average makespan of 24.65 time units (deviation 2.58). Figure 7 shows the resulting makespan over operations when applying the negotiation protocols outlined in this paper. For 6,000 transitions (approximately 1,000 per agent), the process shows results in an averaged makespan of 19.42 time units (deviation 0.57). These results illustrate that the negotiation process leads to a significant improvement of the completion time. Unfortunately, in some cases the negotiation process is getting stuck in sub-optima, and thus the average solution is slightly above the global optimum.

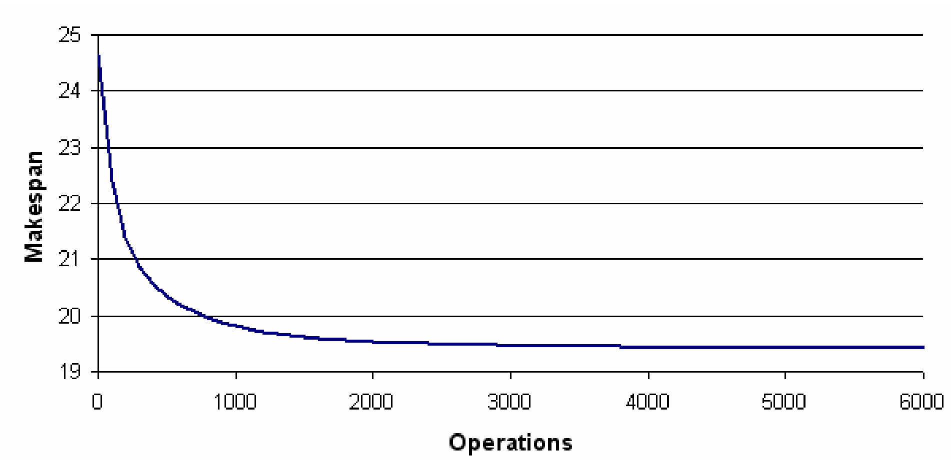

Fig. 7 Overall completion time

The incentives for the agents to take part in the negotiation process are determined by the payoff they will receive. Figure 8 depicts the detailed welfare distribution in the supply web.

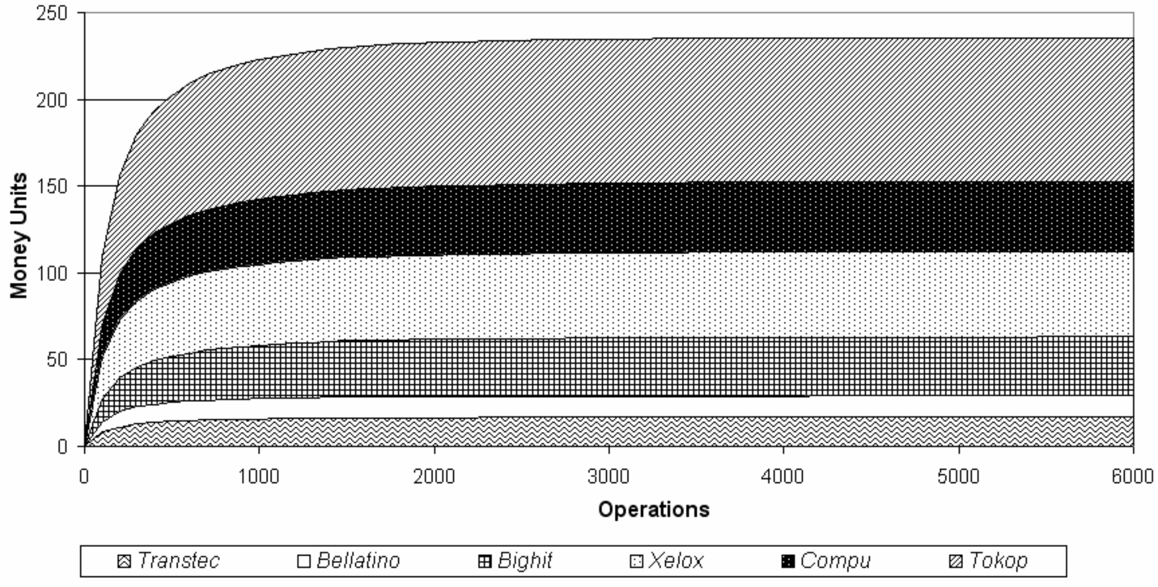

Fig. 8 Payoffs each corporation over time

How can the welfare distribution be explained? The most conspicuous detail is that Tokop Corp. gains the most from all participating agents of the supply web (ignoring the retailer which cannot be compared). It is obvious that this strongly results from its position in the supply chain. Tokop Corp. is the only direct partner of the retailer agent, and thus is always the first to receive payments. The profits decrease upstream the supply chain, whereas the number of jobs seems to be less important (notice that Bighits profits are not as high as one could expect)[6]. The assumption that higher payoffs indicate key positions in the supply chain implies that the dominating players are positioned "downstream".

The estimation of the payoffs for single tasks appears to be highly complex and of very small use for the agents, which have no such information in our scenario.

5. CONCLUSION

Most scheduling systems for supply chain optimization rely on Randomized Search Strategies (RSS) employing price information only valid for a single point in time. The introduction of time dependency via dispositive protocols in our RSS driven approach enables agents to exploit the external effects caused by resource constraints of its supply chain contractors by adapting its production planning. The application of these protocols to a "realistic" scenario shows that their benefits are generally transferable but also give a clue of their limitations. The assumption of individual rationality holds for the system, because the agents act only on their own behalf. Nevertheless miscalculations decreasing the income of an agent can result in agents dropping out of the negotiation process. The ongoing research has to address the incentive problems of these protocols.

Besides higher system flexibility, if rescheduling is required in case of production-failure, time dependant price functions seem to be a suitable medium for the integration of detailed information in the agents' communication process. Related work on the scheduling domain shows that involving learning in agent's behavior is a promising approach to improve system performance and should therefore be the focus of our future work.

[6] The averaged outcome is: Transtec 16.85 MU, Bellatino 12.26 MU; Bighit 34.03 MU; Xelox 49.03 MU; Compu 40.39 MU; Tokop 83.11 MU

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