# Multi-Agent Based Collaborative Demand and Capacity Network Planning in Heterarchical Supply Chains

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## Abstract

In the light of a high division of labor, decentralized coordination shows major importance in today's production and logistics networks and hence is subject to current supply chain management (SCM) research. Especially collaborative planning concepts promise to meet the specific requirements imposed by heterarchical supply chains. This paper demonstrates the multi-agent based modeling and information system-implementation of one concrete collaborative planning concept, namely the collaborative demand and capacity network planning approach. The paper's intention is to substantiate the suitability of multi-agent concepts in decentralized SCM and to strengthen the motivation to combine multi-agent and SCM research.

## 1 Motivation and Problem Description

Today, producing companies are facing a highly dynamic competitive environment which requires effective and efficient business processes in order to meet customer needs adequately. Measures like the concentration on core competencies aiming at this issue have led to a high division of labor and hence a growing number of legally independent participants in the process of providing products to the ultimate customer. The resulting inter-organizational network – commonly denoted as supply chain (SC) – consists of several autonomous companies which cannot necessarily be forced to follow decisions or plans of a superordinate unit. Thus, coordination in such SCs cannot be achieved in the same way as in hierarchical organizations which can be controlled by one dominant actor.

Coordination mechanisms for *hierarchical* SCs have been researched intensely, resulting in the development and practical application of sophisticated supply chain management (SCM) methods, e.g. implemented in advanced planning systems. However, these hierarchical coordination approaches cannot be applied to heterarchical SCs due to the aforementioned decision autonomy of SC actors, combined with the unwillingness to share sensitive private information. Furthermore, companies are generally involved in several networks with conflicting claims, e.g. on a company's resources, which makes central hierarchical plans inappropriate (for details see for example [Breiter *et al.*, 2009]).

Several approaches in current SCM research address the aspects and peculiarities of *heterarchical* SCs in the development of adequate coordination mechanisms (for an overview cf. [Breiter *et al.*, 2009], [Stadtler, 2009]). Especially approaches in the domain of collaborative planning (CP) promise to meet the requirements imposed by heterarchical SCs with respect to decision autonomy and privacy of information. These coordination mechanisms intend to overcome the restrictions of traditional hierarchical planning concepts regarding the practical applicability in heterarchical SCs, while simultaneously improving the SC's performance compared to the uncoordinated situation being present in successive planning approaches.

With respect to the representation and information system (IS) based implementation of suchlike decentralized coordination mechanisms, multi-agent systems (MAS) promise to meet the specific requirements induced by heterarchical structures (cf. [Breiter *et al.*, 2009]). Heterarchical SCs consist of several autonomous actors following their own objectives while being interdependent and linked by physical, financial and informational flows. Thus, interactions between autonomous companies are a major constituent in such networks. MAS provide a natural metaphor for the representation of suchlike complex systems (cf. [Moyaux *et al.*, 2006]) and a technological basis to handle interactions between the SC actors. The suitability of MAS in SCM is, for example, discussed in [Moyaux *et al.*, 2006]. Consequently, MAS provide an elaborate means to represent and implement CP approaches in IS.

This paper presents one concrete multi-agent based modeling and IS-implementation of a CP coordination concept, the collaborative Demand and Capacity Network Planning (DCNP) (cf. [Hellingrath and Hegmanns, 2010]). This approach is suitable for coordinating demanded and offered capacities in built-to-order (BTO) production and logistics networks as existent e.g. in the automotive industry. These SCs are characterized by a huge number of configurable product variants and hence large parts of these SCs – spreading the planning domains of several autonomous companies – follow a BTO production strategy.

On the one hand, the intention of this paper is to demonstrate and substantiate the suitability of MAS concepts in the context of SCM by applying them to the DCNP approach. On the other hand, the presented results are embedded into a more general research on an MAS-based framework for modeling and evaluating arbitrary CP mechanisms called the Framework for Intelligent Supply Chain Operations (FRISCO, cf. [Hellingrath *et al.*, 2009]). The described MAS-based modeling and evaluation of the collaborative DCNP concept therefore constitutes a demonstration of parts of the research on FRISCO.

The paper is structured as follows. Chapter 2 provides an introduction to the collaborative DCNP coordination mechanism. Here, the general idea, intra-organizational planning and inter-organizational interaction and negotiation processes are presented. In chapter 3 the MAS-based modeling of this CP concept is presented. A short introduction to the FRISCO framework (especially its MAS-based modeling component) is provided and the respective MAS-models of the collaborative DCNP are described. Chapter 4 provides details on the proof-of-concept implementation of this coordination mechanism. The implementation is based on the developed MAS-models, i.e. a model-driven development (MDD) approach is followed. The paper concludes with chapter 5, providing an evaluation of the development results and giving an outlook on future research to be conducted in this context.

## 2 Collaborative Demand and Capacity Network Planning

The performance of today's SCs is not determined by a single enterprise's activities, but relies on the whole network's effectiveness and efficiency due to the high division of labor. Current practices show that long-term contracts specify relatively fixed performance agreements between the network's actors, e.g. with respect to the provision of capacity (cf. [Schuh, 2006]). These agreements show a certain inflexibility in the case of demand variations, leading to unsatisfied demand and/or inefficiencies in the production processes due to capacity under-utilization. These aspects are a major issue in BTO production and logistics networks which simultaneously require on time demand fulfillment as well as cost efficient production processes. In case of demand variations, an over- or under-utilization of contractually agreed capacities is likely to occur, leading to late deliveries or inefficient capacity utilization.

The collaborative DCNP concept aims at solving this issue by providing mechanisms to improve the match between demanded and required capacity in inter-organizational BTO production and logistics networks. Three kinds of SC actors that can participate in the coordination mechanism are distinguished: build-to-stock (BTS) suppliers constitute the upstream "ends", original equipment manufacturers (OEM) the downstream "ends" of the coordinated SC. BTO suppliers are intermediaries which source from BTS (or BTO) suppliers and supply OEMs (or other BTO suppliers). The concept is based on the idea of CP and hence coordination is achieved by mutual agreement between these actors without the revelation of private information and loss of local decision autonomy.

On the one hand, the planning concept requires performance agreements between companies which specify the planned capacity provided from a supplier to its customer in the mid-term planning horizon. On the other hand, the concept defines procedures that automatically identify and solve conflict situations, i.e. detect capacity shortages and help to overcome them by a decentralized adaptation of network-wide plans (cf. Figure 1). Demand for capacity is monitored at each stage for each supplier and compared to the previously specified performance agreements in order to be able to identify violations of the agreed capacity corridors.

Besides monitoring the performance agreements, the collaborative DCNP concept defines inter-organizational procedures to resolve occurring contract violations. These procedures are intended to be performed automatically in order to achieve a network-wide, mutually agreed adaptation of capacities to the current demand situation. The concept achieves this decentralized coordination via bilateral negotiations between the actors on multiple stages of the network. The automated negotiations contain the exchange of requests and responses regarding adaptations of plans, i.e. performance agreements, and invoke several local planning processes in order to determine the adaptions' effects on an actor's local plans. Compensation payments for the reservation of additional or cancellation of unnecessary capacities provide a means for the acceptance of locally unfavorable plans. Thus, incentives for participation are integrated into this coordination mechanism, i.e. globally (SC-wide) preferable plans can be achieved in the collaborative DCNP concept.

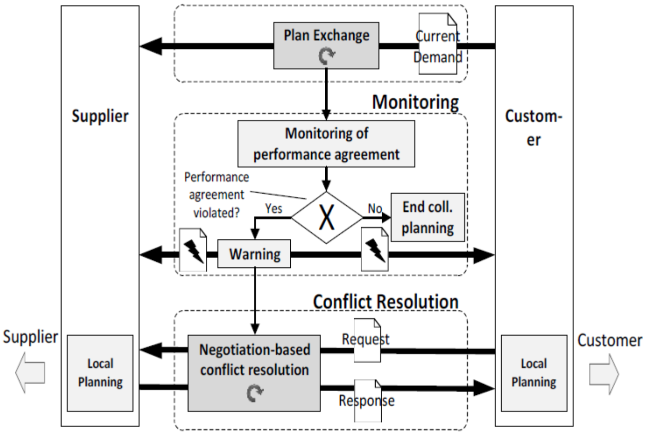

Figure 1: Inter-organizational planning in the collaborative DCNP concept (cf. [Hellingrath and Hegmanns, 2010])

The inter-organizational planning processes adjust the bilateral performance agreements continuously to the current demand situation by solving the aforementioned capacity agreement violations. This coordination process involves multiple rounds of planning and negotiating in order to achieve a network-wide feasible and agreed plan. The high-level description of the collaborative DCNP intra- and inter-organizational processes is depicted in Figure 1.

As discussed in chapter 1, MAS provide the concepts to represent the heterarchical network structure, the interaction processes and the information flows between the different SC participants in the described collaborative DCNP approach. Furthermore, they provide a technological basis to implement the coordination concept in an IS. Thus, the next chapter describes a conceptual model of the collaborative DCNP in a multi-agent based modeling language. Following the concept of MDD, this model provides the basis for the IS-implementation of the collaborative DCNP approach which is presented in chapter 4.

## 3 Multi-Agent Based Model of the Collaborative DCNP Concept

The collaborative DCNP concept shows the characteristics of CP and hence it provides a reference that can be used to exemplary evaluate the FRISCO framework into which the results of this paper are embedded. The general idea of FRISCO is to provide an environment that allows modeling and evaluating decentralized coordination mechanisms – especially CP concepts – for arbitrary heterarchical SCs. The ultimate goal of this research is to pave the way for suchlike coordination mechanisms from primarily being a research domain to practical applications in real SCs. Basically, the framework consists of two parts: a *modeling* and an *evaluation* environment for CP coordination mechanisms. Due to the aforementioned suitability for heterarchical SCs and CP, FRISCO is based on MAS concepts. In order to be able to efficiently cope with differently shaped CP mechanisms beyond the mere modeling, an approach in analogy to MDD was chosen. The goal is to provide an environment that allows modeling the complex structures and processes of CP concepts and furthermore to use these models in order to automatically create executable code for an evaluation of the CP approaches in different scenarios.

Modeling MAS and the automated transformation of models to executable code has been researched intensely in the MAS context and several approaches have evolved (for an overview see e.g. [Nunes *et al.*, 2009]). For the proof-of-concept implementation of the collaborative DCNP coordination approach, the DSML4MAS domain specific modeling language (cf. [Hahn *et al.*, 2009]) was chosen. This language provides the required concepts for a representation and implementation of CP approaches, especially with respect to the graphical definition of complex interaction protocols required by CP and especially the collaborative DCNP approaches.

The abstract syntax of this modeling language is described by an agent-platform independent metamodel called PIM4Agents (cf. [Hahn *et al.*, 2009]). The concrete syntax of this modeling language has been specified and implemented by means of the Eclipse Modeling Framework (EMF), i.e. graphical modeling of complex MAS is supported by the DSML4MAS environment. Furthermore, translation rules have been defined transforming conceptual models to executable code which can be run on the FIPA compliant MAS platform JADE.

The DSML4MAS relies on several views on the different aspects of MAS (for details see [Hahn *et al.*, 2009]). By means of these views, the DSML4MAS development environment provides all concepts that are required to formally model the collaborative DCNP approach. All required views were developed and instantiated in order to model the concept. The most important models that describe the CP concept are depicted in the following.

As mentioned in chapter 2, collaborative DCNP distinguishes three types of actors (BTS/BTO suppliers and OEM) that can participate in the coordination mechanism. Transferred to the MAS model in DSML4MAS, these are represented by three agents in the so called "agent view" (cf. Figure 2). The collaborative DCNP coordination mechanism relies on two roles that can be taken on by its participants: *Supplier* and *Customer*. These roles are reflected in the agent view by permitting the agent types to act in the respective role. The OEM determines the downstream "end" of the production network and is therefore only permitted to act as a *Customer*. Analogously, upstream the BTS supplier constitutes the last actor in the coordinated part of the SC, i.e. is only permitted to be a *Supplier*. The multi-tier support of the collaborative DCNP concept is facilitated by allowing BTO suppliers to act as both, *Suppliers* and *Customers*. Besides the assignments between agents and roles, the agent view is furthermore used to define plans that can be used by the agents, i.e. it allows for modeling the internal agent behavior. Plans that are directly connected to an agent via a *uses* relation are triggered in the instantiation phase. Thus, the agent diagram depicted in Figure 2 shows the startup plans that initialize the agents' data structures. Besides these three plans, the agent diagram contains a multitude of plans that describe the agents' local behavior throughout the collaborative DCNP concept (not depicted in Figure 2).

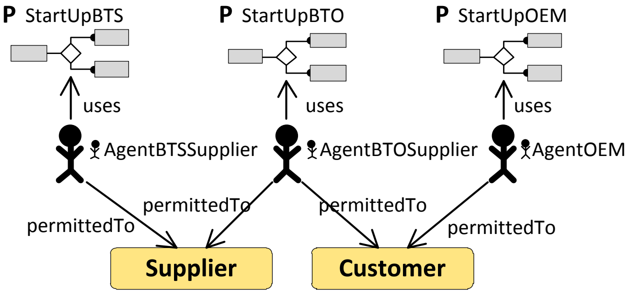

Figure 2: Agent view on the collaborative DCNP concept (excerpt)

The next step in modeling the collaborative DCNP concept is the definition of interactions that can take place in the MAS, i.e. in this case between the *Customer* and *Supplier* roles. This requires the assignment of the two roles to an organizational structure, which is modeled by an organization called *OrganizationDCNP* in the "MAS view" (see Figure 3, left). The *OrganizationDCNP* represents one stage of the SC being coordinated by the collaborative DCNP concept. Modeling the organization is the prerequisite for the definition of interaction mechanisms taking place in the organization as the participating roles are defined. Besides the organizational assignment, the MAS view also contains a definition of the environment (not depicted in Figure 3), especially containing descriptions of the messages being communicated in the MAS.

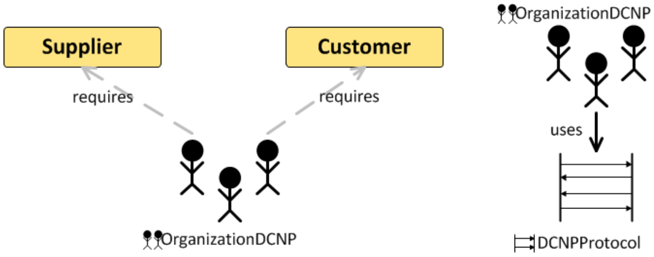

Figure 3: MAS (left) and organization (right) views (excerpts)

Besides the MAS view, an “organization view” is required to define which interactions can be performed within the organization i.e. one stage of the SC. In the collaborative DCNP case, these interactions are modeled by a protocol called *DCNPProtocol* – described in detail below – which contains all communication steps of the coordination mechanism (cf. Figure 1). Therefore, a *uses* relation between the *OrganizationDCNP* and the *DCNPProtocol* is modeled in the organization view in order to allow the application of this protocol to the different stages of the SC being coordinated (cf. Figure 3, right).

Following the inter-organizational communication defined in the collaborative DCNP concept, the *DCNPProtocol* can be divided into three major phases: communication of plans, conflict identification and the reaction upon conflict situations including negotiation processes for potential plan adaptions (cf. Figure 4). The protocol uses Agent Communication Language (ACL) messages in the communication process and prescribes the order of message exchange in the different interaction and negotiation phases. Within DCNP a set of negotiation states and message types is defined that were implemented by respective state transitions and message exchanges in the *DCNPProtocol*.

The inter-organizational coordination is started by the actor called *Initiator* who sends an *activation signal* to the *Participant* and thus initializes the whole coordination process. The initiator is a customer and hence initially an OEM in the coordinated SC. Since the concept covers multiple tiers of SCs, also BTO suppliers (as customers of BTS- or other upstream BTO-suppliers) may initiate the *DCNPProtocol* in order to coordinate their supplier network. The next protocol step is the exchange of the consumption plan i.e. the intended capacity utilization in the planning horizon. This results in a state transition of both actors (represented by so called sub-actors *UpdatedCustomer* and *UpdatedSupplier*). The exchanged plans are compared with the performance agreement in order to distinguish between regular and conflict situations. In case of no conflicts, the *DCNPProtocol* is terminated (indicated in Figure 4 by an arrow defining the state transition to the finalization phase).

In case of a performance agreement violation, the actual negotiation protocol for conflict resolution is started. The negotiation protocol requires several state transitions and local planning invocations, especially in order to account for the different stages of the conflict resolution process (e.g. adaption request sent, temporary reservation made and final reservation accepted). Due to the support of multi-tier networks, the *DCNPProtocol* is processed in a recursive manner. This allows BTO suppliers to coordinate their supply network before accepting definite changes to performance agreements on the customer side. After processing the negotiation protocol and coordinating the supply network (or in

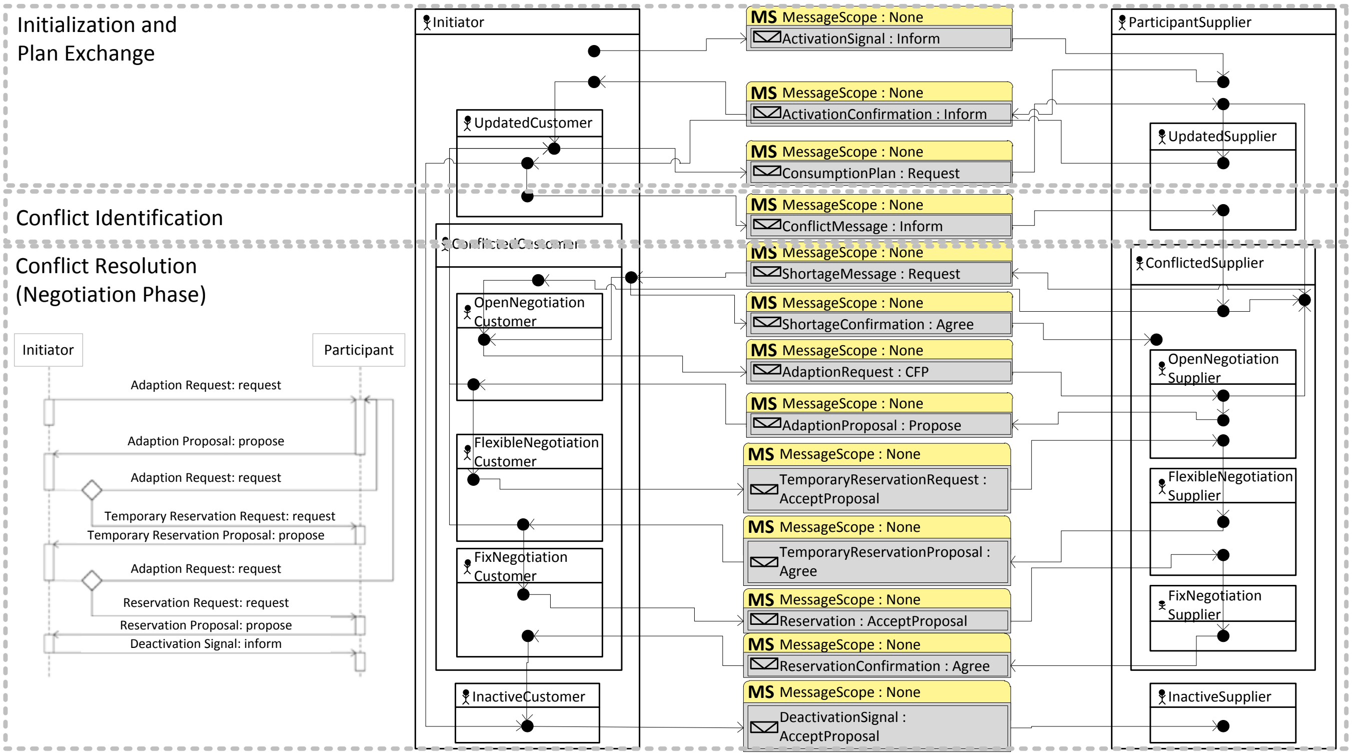

Figure 4: Phases in the collaborative DCNP concept and corresponding message exchanges in the protocol.

case of no conflicts), the *DCNPProtocol* terminates by sending a *DeactivationSignal*.

The collaborative DCNP concept defines several intra- and inter-organizational business processes that are performed for coordinating the SC. As mentioned above, these processes are modeled by defining plans that describe the behavior of agents in detail. These plans control the internal behavior and therefore connect local planning and decision processes to the inter-organizational communication processes as defined in the *DCNPProtocol*. Thus, besides the internal tasks to be performed at the different stages of the coordination process (plan exchange, monitoring and conflict resolution), the required procedures, with respect to production planning (primary demand determination, adjustment planning, local deficit calculation and proposal formulation) and procurement planning (secondary demand determination, shortage management and deficit calculation), were modeled in several plans in the agent view.

Modeling the intra- and inter-organizational processes of a CP concept by means of DSML4MAS constitutes a large part of the modeling process in the framework that is pursued by our research.[1] Since an MDD approach is followed, these models can be translated into source code allowing the execution of the coordination concept in a concrete SC scenario in the JADE runtime environment. The following chapter therefore describes further required steps in implementing and evaluating the collaborative DCNP concept.

## 4 Implementing the Collaborative DCNP Concept

The models of the collaborative DCNP in FRISCO define the basis for the implementation in an MAS runtime environment. The DSML4MAS development environment provides several translation rules that ultimately allow the generation of executable (agent) source code.

The models of the MAS as described in the previous chapter conform to the PIM4Agents metamodel (cf. [Hahn *et al.*, 2009]). The developers of the DSML4MAS environment defined mapping rules that allow a translation of corresponding platform independent MAS models to platform specific models and furthermore specified translations of the platform specific models to executable code. These two transformation steps therefore provide a mechanism to automatically generate JADE compliant agent code (in Java) based on the graphical models of the collaborative DCNP. In addition, the MDD approach allows for the inclusion of custom source code into the automatically generated code (e.g. in order to invoke local optimization) which is not changed by the transformation engine in case of model modifications.

Besides the models of the collaborative DCNP described in the previous chapter, an implementation of this concept in one concrete SC scenario requires the structural definition of a SC i.e. the assignment of specific actors to their respective roles in the coordination mechanism. This scenario definition is specified in the "deployment view" of DSML4MAS. Figure 5 shows an example of a deployment diagram which is used to specify a two tier SC consisting of one OEM, one BTO supplier and two BTS suppliers.

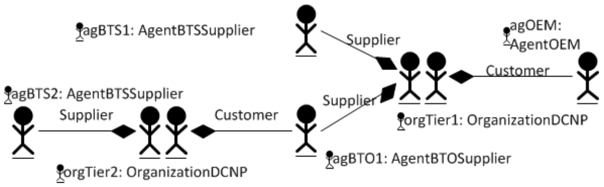

Figure 5: Scenario definition in the deployment view

The four agent instances are assigned with their respective roles to two organizations (*OrganizationDCNP*) which were specified in the organization view (see descriptions in chapter 3). These assignments define that the agents participate in the collaborative DCNP concept, i.e. the interactions in these organizations follow the *DCNPProtocol*. Since one *OrganizationDCNP* represents one stage of the SC being coordinated, two organizations are modeled in the deployment diagram in order to represent a multi-tier structure. The OEM/1st-tier relationship is therefore modeled by an organization called *orgTier1*; the 1st/2nd-tier relationship respectively by *orgTier2*. Based on this deployment diagram the agent source code is generated by the DSML4MAS transformation rules. The results represent the SC scenario and can be deployed on the JADE platform afterwards. The agents are capable of performing the collaborative DCNP concept in a runtime environment allowing its evaluation.

In order to show and evaluate the correct operation of the collaborative DCNP concept in the scenario, the MAS was extended by a mechanism to simulate the business processes and hence the DCNP protocol execution. This was achieved by modeling a "simulation protocol" (also in DSML4MAS) which all agents participate in and which is controlled by a "simulation agent". This allows triggering the agents each period, i.e. the intra- and inter-organizational processes of the collaborative DCNP are executed in the scenario consecutively over multiple periods.

Figure 6 shows a screenshot of the graphical visualizations of two agents which perform the collaborative DCNP concept in the exemplary SC: the agent depicted on the left side represents the BTS supplier on tier 2 (*agBTS2*). The agent interface shown on the right side in Figure 6 represents one of the two suppliers on tier 1 (*agBTO1*). Thus, *agBTO1* is supplied by *agBTS2* and in turn supplies the OEM (*agOEM*). One period was simulated, i.e. the ultimate customers requested products from the OEM, which afterwards communicated the resulting capacity demand to its suppliers (including *agBTO1*). Conflict situations were identified and the collaborative DCNP coordination mechanism started. Throughout the coordination processes, network-wide adaptations of the capacity corridors were

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[1] Besides the described models it is furthermore necessary to define the SC agents' knowledge in an ontology. This ontology is provided by the framework and already contains many SCM-related concepts to describe SCs, e.g. for sourcing relations, bill-of-material, resources etc. (cf. [Hellingrath *et al.*, 2009]). Extensions being necessary in this part of the framework in order to model a CP approach will not be described in detail here.

negotiated and agreed upon in order to meet the capacity demand as good as possible. The thick lines indicate deviations from the original performance agreements (thin lines) that result from the automated negotiation processes. The capacity demand from the *agOEM* required adaptations to the performance agreement between *agBTO1* and *agOEM* (right side in Figure 6). Changes to the capacity corridors of *agBTO1* furthermore affected its supply network, i.e. also *agBTS2*. This agent therefore had to increase the capacity corridors of its performance agreement with *agBTO1* in the planning horizon (left side in Figure 6).

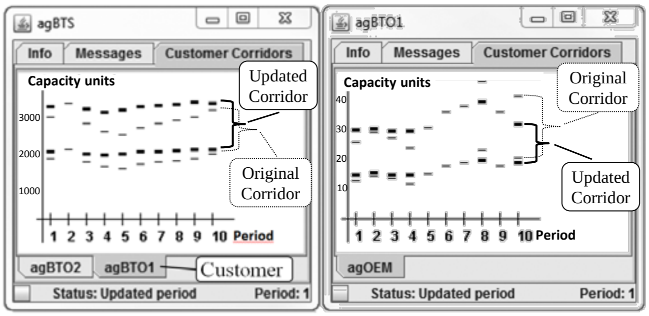

Figure 6: Annotated screenshot of agents in an exemplary scenario

In addition to the results of the coordination mechanism in form of agreed plan adaptations, the conducted inter-organizational communication processes were analyzed. By means of the JADE “sniffer agent”, the messages exchanged were traced proving the correct operation of the *DCNPProtocol* over multiple tiers. These analyses therefore allow a first evaluation of the collaborative DCNP concept. Apparently, plan adaptations were performed in order to improve the match between demanded and offered capacity in the network. However, the evaluation component of FRISCO has to be further extended for a transparent and comprehensive monitoring of CP and SC performance indicators.

## 5 Conclusion

The research presented in this paper has two goals. First, the suitability of MAS concepts in the domain of CP and decentralized SC coordination is intended to be substantiated. This goal was achieved by modeling and implementing the collaborative DCNP coordination mechanism by means of concepts and methods from the MAS research domain. The structure of heterarchical SCs and the crucial inter-organizational processes in CP approaches proved to be reasonably representable by means of an MAS modeling environment. The different views provided by the used DSML4MAS allow an elegant modeling of all intra- and inter-organizational business processes of the collaborative DCNP concept. Based on these models, different SC scenarios can be defined to which the concept is easily applicable. The automated code generation from MAS models to executable Java code provides a major advantage in the consistent and re-usable implementation of CP concepts.

The second goal of the presented research addresses the usage of MAS concepts in a more general framework for modeling and evaluating arbitrary decentralized coordination mechanisms in heterarchical SCs. The implemented proof-of-concept strengthens the argumentation for this approach since requirements on the framework were shown to be satisfiable by an MAS-based concept. However, the framework is still under development and will be extended in order to allow both an efficient modeling and evaluation of arbitrary CP approaches. This especially requires research on the measurement of CP performance indicators and an extension of the framework’s evaluation capabilities. In addition, the methodology that guides the CP modeling and evaluation processes will be elaborated further.

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