A Multi-Agent Decision Support System for Dynamic Supply Chain Organization

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Abstract In this work, a multi-agent system (MAS) for supply chain dynamic configuration is proposed. The brain of each agent is composed of a Bayesian Decision Network (BDN); this choice allows the agent for taking the best decisions estimating benefits and potential risks of different strategies, analyzing and managing uncertain information about the collaborating companies. Each agent collects information about customer's orders and current market prices, and analyzes previous experiences of collaborations with trading partners. The agent therefore performs a probabilistic inferential reasoning to filter information modeled in its knowledge base in order to achieve the best performance in the supply chain organization.

1 Introduction

In this paper, we present a decision support system for companies involved in the organization of a supply chain. In such a complex environment decisions must be made quickly, analyzing and sharing several information with multiple actors [1].

A supply chain management system includes several entities: the different companies involved in the supply chain and, for each company, different entities specialized in the accomplishment of specific business tasks. Such scenario makes urgent the realization of new tools for effectively retrieving, filtering, sharing and using the information flowing in the network of suppliers/customers. Supply chains are constantly subject to unpredictable market dynamics, and in particular to the continuous changes in prices and also in commercial partnerships, which may become more or less reliable. The uncertainty that characterizes these changes can affect the supply chain performance and should be properly handled [9][10].

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Multi-agent systems may be particularly useful for modeling supply chain dynamics [2]. The entities involved within a supply chain can be represented by agents able to perform actions and make autonomous decisions in order to meet their goals [3][4]. Supply chain organization is, therefore, a distributed process where multiple agents apply their own retrieval and filtering capabilities. Multi agent systems (MASs) provide an appropriate infrastructure for supporting collaboration among geographically distributed supply chain decision-makers [8]. As an example, in MASCOT system [7] a set of agents help users distributed across multiple companies to collaborate on the development and revision of supply chain solutions through an open and uniform communication and coordination interface.

Many works highlight the importance of a dynamic configuration of supply chains for market changes adaptation. In [8] the authors after a discussion about information related issues in a dynamic supply chain, propose the definition of models based on the integration of agent technology and Petri networks to improve information flows and highlight potential risks for supply chain actors.

In [6], a machine learning algorithm based on decision tree building allows for the choice of the best node at each stage of the supply network analyzing the combination of parameters such as price, lead-time, quantity, etc.

In this work, we envision a system where the supply chain can be automatically organized maximizing the utility of the whole group of collaborating partners. The success of the established collaborations depends on the capability of each company and of the whole group to adapt to the changes in the environment they work within. Adapting their strategies and behaviors, the whole group of partners is able to exploit new solutions and configurations that can assure the production of high quality products and can guarantee a profit for each partner.

Other works focus on uncertainty problematics in the organization of supply chains [9],[10], [11]. In particular, in [11], a theoretical model, based on an extension of Bayesian Networks models, is used to formalize supply chain agents' interactions during an order fulfillment process. The direct supply-demand relationships between pairs of agents are modeled as directed causal links, because the failure of a supplier to fulfill its commitments may affect the commitment progress of his customers. The information sharing between agents is modeled as belief propagation. The extended Bayesian Belief Network model proposed by the authors allows the agents to perform strategic actions, such as dynamically select or switch the suppliers, or take decisions to cancel a commitment based on its related expected utility function.

In contrast of [11], in the proposed system we exploit the advantages of Bayesian Decision Network (BDN) models. Each agent of the chain has its own BDN where formalizes its beliefs about the reliability of commercial partners, based on trade relationships established during the past business experience. The information arising from each network is used for configuring the entire supply chain.

The system we propose is made of a community of intelligent agents able to provide support in supply chain decision processes. Each agent is responsible for decision-making processes relating to a particular company. To accomplish this goal each agent has to retrieve information necessary for decision making, incorporating them in its own knowledge base. Decision making is not a simple activity but a process leading to the analysis of several variables, often characterized by uncertainty, and the selection of different actions among several alternatives. For this reason, the brain of each agent has been modeled by means of a Bayesian Decision Network (BDN)[5]; this choice allows the agent for analyzing uncertain information and estimating the benefits and the potential risks of different decisional strategies.

The paper is organized as follows. In Section 2 the proposed system is described, while in Section 3 a case study is reported; finally Section 4 reports conclusions about the proposed system and future works.

2 Proposed System

In this paper, we make the assumption that each company is represented by an agent, and we focus on the information retrieval and filtering process performed by each agent to organize a supply chain.

Figure 1 shows how the supply chain creation process is triggered. We assume each agent in the supply chain analyses the information provided by the informative system of the company it works on behalf of. Such informative system constantly updates the agent about the current available resources, the productive capabilities, the time required for developing the business processes and other useful information. The supply chain decisional process starts when a new order arrives to a company. The agent responsible for that company will then trigger a decision-making process aimed at the supply chain building. This process leads in turn to the creation of sub chains, performed by other agents involved in the fulfillment of the order. To create its own sub-chain each agent queries the informative system of its company.

An agent representing a certain company in the supply chain can act as supplier if the company is a provider of some material, or as supplier/customer if the business activity of the company requires other products or raw materials from other companies in the chain.

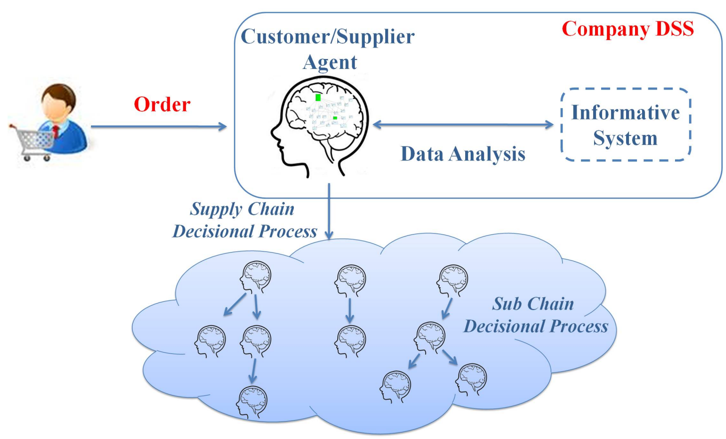

Fig. 1 In the proposed system, a set of agents collaborates to fulfill the customer's order. The agent receiving the order triggers the supply chain organization process that is developed hierarchically within the group of collaborating companies.

2.1 Dynamic Supply Chain Organization

During the supply chain organization process, each agent can receive an invitation to join the chain as supplier and, based on its actual resources, productive capabilities and economical convenience, it can decide if joining the chain or no. To collaborate in the chain, the agent can ask other agents for products/services it needs for its own business process. In this case, it acts as customer and invites other agents to join the chain for satisfying a certain order. In practice, before joining the supply chain, the agent needs to organize a sub-chain for its own business process. Once an agent knows it can join the supply chain, it replies to the invitation informing about its availability and the conditions it wants to impose for being part of the collaboration (for example price and temporal conditions). Therefore, a supply chain is the result of a set of negotiations among the agents belonging to the same group. To reach the consensus, two different kinds of information flow across the agent network. As depicted in figure 2, the up-down information flow represents the invitations sent to agents for being part of the supply chain, while the bottom-up information flow represents the information flowing from suppliers to customer about their conditions to join the supply chain.

During the negotiations, all the agents are in competition one each other; their behavior can be oriented to maximizing their business volume constrained by the quality of the final product, their productivity capability and the minimum profit they want to get. The supply chain can be built choosing all the agents that, with the highest probability, could assure the success of the final supply chain and would collaborate to satisfy the final customer's order. In the following, we assume that the entire supply chain can be modeled as a tree; at each level, a sub-tree represents a sub-chain. In our formulation, at each node of the tree an agent provides a particular goods or service needed at higher levels to provide the product required by the customer. However, the production of this goods/services can require the cooperation of other agents. Therefore it can be necessary to establish a set of collaborations with other agents, i.e. a new sub-chain. The organization of the entire supply chain reduces to recursively organize each sub-chain as showed in figure 2. The problem of organizing a supply chain is therefore addressed by dividing it into sub-problems of lower complexity. The entire supply chain can be organized considering sub-optimal solutions at each node of the tree. Whilst in general the solution will not be globally optimal, under the assumption of independence of the sub-tree, the final solution will be optimal. This assumption does not limit the applicability of our system because it is reasonable to assume that at each node of the supply chain independent business processes would be developed.

2.2 Supply Chain Decisional Process

The supply chain organization requires the selection of agents whose cooperation can ensure the success of the entire supply chain. It is necessary to adopt strategies that take into account the uncertainty of the environment in which the agents work. In fact, the establishment of a supply chain is not a deterministic process. Factors such as delays in delivery – for example due to an excessive geographical distance of the companies the agents represent –, the reliability of a supplier and consequently the failure to meet his commitments could determine a failure for the supply chain.

To take into account the uncertainty of the business process, in our system each agent adopts a Bayesian Decision Network (BDN) to represent explicitly considerations about cost-benefits associated with each strategy in the decision-making process.

In our system, each agent can assign a degree of uncertainty to the success or failure of a particular configuration for a supply chain. To develop its business process, an agent retrieves the information about all the suppliers available to join its own chain and reasons on the collected information; then, by means of a BDN, the agent filters the suppliers and retains only those able to organize the best sub-chain.

The probabilities of the network may be a priori known or on-line learnt based on strategies chosen by each agent. In this sense, several strategies can be adopted, especially depending on the type of market. Business decisions can be taken in relation to parameters of convenience, as generally done in case of wide consumer products, or considering other factors such as the prestige, the competitiveness or the brand of the potential suppliers, as happens in a market of luxury or highly differentiated products. Different strategies can be appropriately modeled in the BDN.

2.2.1 Supply Chain Decision Network

Figure 3 shows an example of decision network used by each customer agent to organize its own sub-chain.

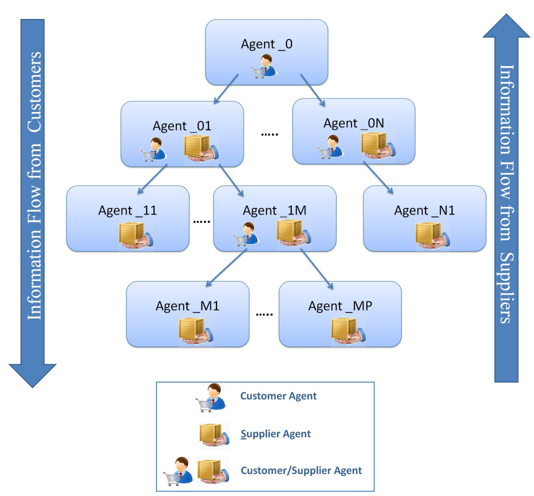

Fig. 2 A Supply Chain can be organized hierarchically. Each agent can build a sub-chain to develop its own business process. Each agent behaves as supplier towards the higher level in the tree, and as customer for the agents at the lower level in the tree. The image shows the two different information flows within the agent network.

The strategy of each agent is to compare the reliability and the price proposal of different suppliers. In particular, to take into account the reliability of an agent to meet its commitments when involved in a collaboration, each agent is associated with a "reputation". Based on its past experience or on specific adopted strategies, each agent associates each supplier with a certain reputation that it can adapt over time. In practice, the reputation represents how much the agent trust in its suppliers. For example, it is possible to on-line learn such value by measuring the number of times a supplier has fulfilled its commitments and/or evaluating the quality of the collaborations in which the supplier has been involved (by analyzing a set of parameters such as the product/service quality and time delivery), or considering the supplier degree of specialization or expertise in the field.

In the specific example, it is assumed that agent needs to buy two different types of materials to manufacture its product. Each material is associated with a list of possible supplier agents. The reputation node (which shows the reputation associated with the supplier – *low, medium, high, not available*) and the offer node are conditioned on the choice of the supplier; the offer node is modeled by a deterministic node (*SupplierMaterialOffer*) representing the cost of the offer proposed by the supplier (*sufficient, fair, good, not available*). This value may be determined by comparing the received offer to the market price and/or evaluating the quality and characteristics of the offered products.

The reputation associated with a supplier agent influences the commercial transaction to acquire the specific material, represented by the node *TransactionStatus*. The reputation and the offer jointly determine the utility associated with the transaction between the customer agent and the selected supplier agent (utility node *TransactionUtility*). The value of the expected utility is the expected value associated with the offers according to the reputation probability distribution. The Transaction utility nodes for all the needed materials are used together to determine the utility of the entire sub-chain. The Transaction probabilistic nodes for raw materials, instead,

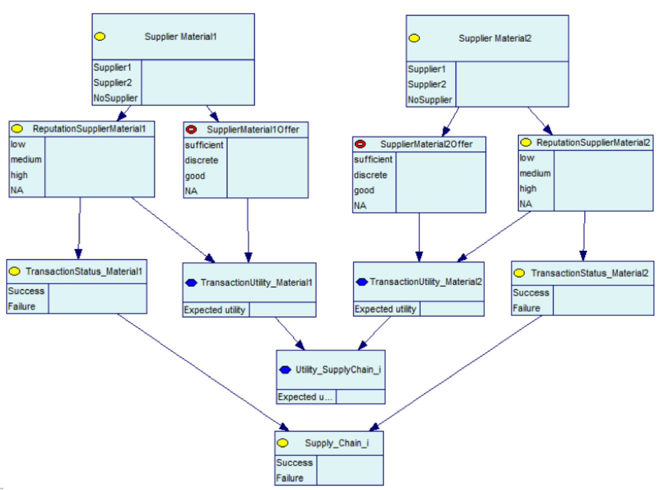

Fig. 3 Agent Decision Network for selecting the suppliers that maximizes the utility associated with the supply chain. In the figure, only two kind of materials have to be bought.

influence the probabilistic node *Supplychain*, which expresses the probability that a supply chain can be successfully established.

Through the proposed BDN, the decision analysis is performed directly comparing the utility values corresponding to different choices ensuring the success of the supply chain. We stress the BDN parameters implement the strategy that each agent wants to adopt when assembling its supply chain. Parameters of the utility nodes for each agent can be devised by a knowledge engineer according to the sale manager guidelines in order to represent the strategy for the company the agent works on behalf of.

2.3 Dynamic Behavior of Agents over Time

Although the agents may adopt different strategies, in our formulation we assume each agent chooses whether to participate in the organization of a supply chain based on the available resources. If it decides to join the chain, the agent sets the selling price taking into account constraints related to the minimum profit it wants to get from the transaction, and its experience in previous negotiations. Therefore, in our system each agent decides whether to increase or decrease the selling price based on the outcome of the offers in previous transactions within a given time window. If the agent has not been selected for joining a supply chain at a certain selling price then, at the next negotiation, it decreases the selling price (constrained by the costs necessary for production). Conversely, if its previous offers have been accepted at a certain price, it tries to slightly increase the selling price in order to maximize its profit. As a consequence, in this scenario, the agents adopt a lower price strategy, where prices tend to decrease and agents become as more competitive as possible.

Let P_m be the minimum selling price to cover production costs and ensure a minimum profit, and P_M the maximum selling price the agent knows it is risky to sell to (this price could be set by the customer of the agent). The selling price varies according to the number of times k the agent has joined a supply chain in the time window T. In particular, the selling price P varies according to the following:

$$P = \max(P_m, P^*) \tag{1}$$

where

$$P^* = \begin{cases} \min(P_{t-1} + \Delta P; P_M) & \text{if } k \geq \tau \\ P_{t-1} - \Delta P & \text{if } k \leq \gamma \\ P_{t-1} & \text{otherwise.} \end{cases} \tag{2}$$

In the previous formula, P_{t-1} is the selling price offered at the last negotiation, while ΔP is a priori known value representing how much the selling price is increased/decreased. τ represents the threshold value to determine after how many successful transactions in T the price would be increased; conversely, the threshold γ is the maximum value of k for which the price should be reduced.

Although more complex strategies could be applied, the one just described allows agents for dynamically adapting to the environment in which they operate favoring a free competition among the partners within the same group.

3 Experimental Results

To evaluate the system, we considered the simple case where the supply chain can be represented by a binary tree and each agent can have no more than two different suppliers for each material it needs to buy. As discussed in Section 2.2.1, it is possible to learn agent reputation considering the success of the negotiations among agents through the time. Here, for the sake of demonstrating our approach, i.e. adopting a BDN for taking decisions about the supply chain organization, we assume agent reputations are constant across time and study how the negotiations are carried on among the agents. We empirically demonstrate that, as consequence of the supply chain organization outcome and, therefore, of the decisions taken by each agent, at each negotiation the agents change the offered price in order to join more supply chains as possible.

To implement our Multiple-Agent System, we adopted the Java Agent DEvelopment Framework (JADE) [12], that simplifies the development of distributed agent-based systems. The BDN has been implemented by GeNIe [13], that offers a simple environment to design decision-theoretic methods. We also implemented simple wrapper classes the agents can use to interface with GeNIe.

We simulated a network composed of 21 different agents as showed in figure 4. We are assuming the agents have to buy only two materials, and for each one they would contact only two suppliers. Of course, this configuration has meant for demonstrating the validity of the proposed approach, but in real cases more complex scenarios can be handled. We also assume each agent offers its product at a certain price computed based on a certain strategy, i.e. the one presented in Sec. 2.3.

Let $\{S_i\}_{i=1}^{5}$ be the set of agents that can act both as supplier and customer within the supply-chain; therefore, they need to organize their own sub-chains. Let $\{A_j\}_{j=1}^{16}$ be the set of agents that have the role of suppliers within the supply chain; these agents do not need to organize any supply chain for their business processes. Let $\{P_k\}_{k=1}^{10}$ represent the products that are sold/bought within the agent network to assemble the supply chain.

In figure 4, the agent S_1 has the role of supplier to the final real customer and assembles the main supply chain for satisfying the incoming orders. Agent S_1 provides the product P and needs to buy two different kinds of materials: P_1 and P_2. Then, it sends an invitation to join the chain to its own suppliers, that are S_2 and S_3 for the material P_1 and S_4 and S_5 for the material P_2. To provide the product P_2, the agent S_2 needs the materials P_3 and P_4 and, therefore, it contacts the corresponding suppliers: A_1 and A_2 for P_3, and A_3 and A_4 for P_4. This kind of hierarchical structure is repeated for each agent at the second level. In this specific scenario, only the agents at the first and the second level of the tree decide to organize a supply chain and, therefore, they use the proposed decision network for choosing the configuration of suppliers that would guarantee their maximum utility.

3.1 An example of Supply Chain Decision Making

The supply chain organization requires a set of negotiations among the agents to exploit possible collaborations and choosing the one that maximizes the agent utility. A negotiation can be modeled as an exchange of messages among agents that communicate their availability to join the chain at certain conditions, i.e. prices, quantities and time.

The selection of the agents joining the chain is done considering the utility associated with the supply chain; based on the value of reputation and cost, it is possible that a supplier offering an higher price is selected because of its reputation. For example, let consider the scenario represented in table 1. Two suppliers with the same probability distribution of the reputation (*Reputation low, medium, high and NA*) are selling the same material at two different prices that the agent considers discrete and good respectively. In this case, the BDN permits the agent to select the most convenient price. This can be easily seen comparing the utilities associated to each transaction.

In the case represented in table 2, two suppliers with different probability distribution of the reputation are selling the same material at two different prices that the agent classifies as discrete and sufficient respectively. In this case, whilst the first supplier is offering the most convenient price, the agent chooses the supplier with the better reputation distribution.

Table 1 Scenario 1 – Supplier selection in case of same reputation distribution and different offers.

Nodes	*Reputation Low*	*Reputation Medium*	*Reputation High*	*Reputation NA*	*Offer*	*TransactionUtility*
Supplier 1	0.33	0.33	0.33	0	discrete	6
Supplier 2	0.33	0.33	0.33	0	good	7

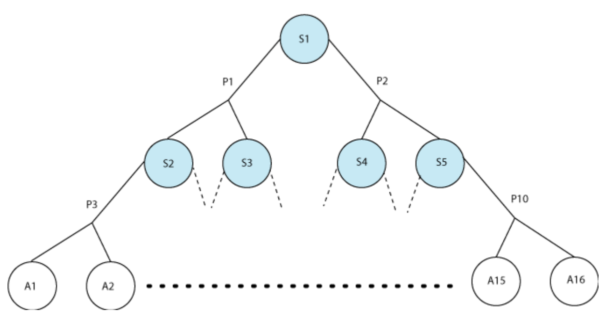

Fig. 4 The figure shows the environment simulated for demonstrating the validity of the proposed system. Each node in the tree represents an agent. Only five agents need to build sub-chains. To organize the supply chain, agent S_1 needs to buy products P_1 and P_2. Therefore, it has to choose between S_2 and S_3 and between S_4 and S_5. On the other hand, S_2 needs to organize its own sub-chain before raising an offer to S_1. It needs to buy P_3 from the agent A_1 or A_2 and the material P_4 from the agent A_3 or A_4. Every agent of second level works similarly.

Table 2 Scenario 2 – Supplier selection in case of different reputation distributions and offers.

Nodes	*Reputation Low*	*Reputation Medium*	*Reputation High*	*Reputation NA*	*Offer*	*TransactionUtility*
Supplier 1	0.5	0.5	0	0	discrete	6
Supplier 2	0	0.5	0.5	0	sufficient	7.5

3.2 Price Variation based on Past Experience

As explained in Sec. 2.3, each agent of our system changes the selling price considering its experience in past collaborations. As all the agents will change their prices, the conditions to organize the supply chain are dynamic and, therefore, it is possible to observe how the strategies adopted by the agents affect the price of the product provided by the whole supply chain and by each sub-chain.

To these purposes, we run 100 simulations where the agents negotiate to organize a supply chain and then automatically modify their offers in order to increase the chance of being selected for the supply chain creation and to maximize their profit. To show how the agents modify their own behaviors, we focus on negotiations about the same product.

Let us consider the competition between suppliers S_4 and S_5 for the product P_2. Assuming that the two agents have the same reputation distribution, then the customer agent will select the supplier based on the best offer. Across time, to join the chain, agents S_4 and S_5 decrease their selling prices in order to be more competitive (see Fig. 5). The same scenario but with different reputation distributions for the agents is showed in Fig. 6. Now S_4 decreases its offered price faster than S_5 to reduce the reputation gap. When S_5 decreases its price too, the agent S_5 is preferred because of its reputation.

Let us consider the competition between suppliers S_2 and S_3 for the product P_1. We consider the case when S_3 always has a better reputation distribution. In this case the agents have a different minimum price but the lowest is not always selected because of the worst agent reputation(see Fig. 7). In all the plots in Figs. 5, 6 and 7, the markers at each run correspond to the agent that has been select to join the supply chain.

4 Conclusion and Future Works

In this paper we presented a decision support system for the automatic organization of a supply chain. In our formulation, a supply chain can be modeled hierarchically as a tree where each node represents a company providing a certain product/service to the higher level and buying products/services from the lower level. In practice, each sub-tree models a sub-chain. We employed agents for representing the companies involved in the supply chain organization and equipped each agent with a BDN they can adopt to filter information flowing in the customer/supplier network.

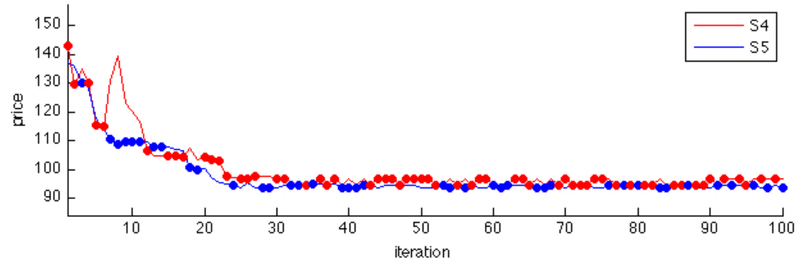

Fig. 5 The figure shows how the price of the product P_2 offered by S_4 and S_5 changes across time. The agents have the same reputation distributions and the supplier offering the lowest price is selected. Therefore, agents tends to decrease their prices to be more competitive.

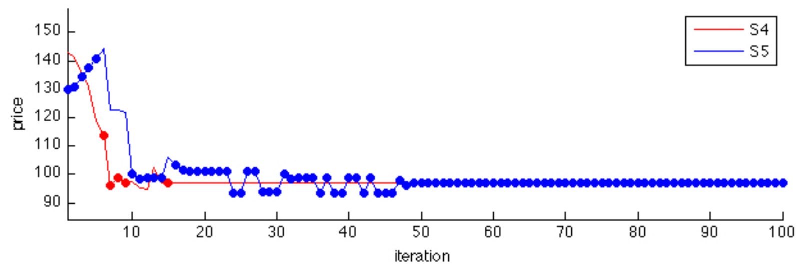

Fig. 6 The figure shows the plot of the product P_2 price offered by S_4 and S_5. Agent S5 has a better reputation distribution, and when a minimum tradeoff price is reached it is always selected from the higher level.

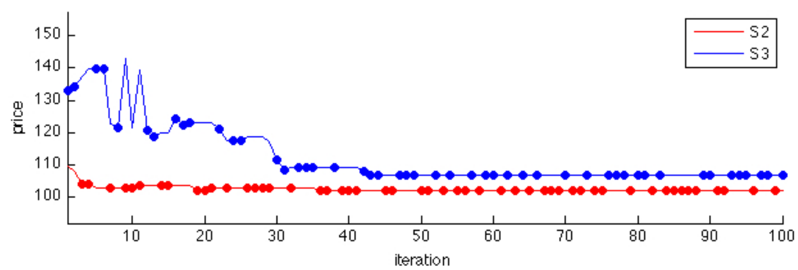

Fig. 7 The figure shows how the prices of the product P_1 offered by S_2 and S_3 changes across time. In this case, the agents have different reputation distributions; the supplier selection is done based on the transaction utility taking into account both the price and the reputation.

In particular, the proposed BDN explicitly models the uncertainty of the information owned by the agent and related to the dynamic environment the agent works in. Moreover, our BDN formalizes the concept of reputation of the suppliers and permits to select those suppliers that would guarantee the best utility for the agent and the success for the whole supply chain.

We presented a simplified model that can be further improved through the collaboration between the knowledge engineer and a domain expert. The domain expert will identify the best decision criterion to consider in the supply chain management and their role. After a careful analysis a general model will be defined and customized by each company according to its management policies. Therefore in future works, more attention will be paid in modeling the decisions of each agent of the chain. In particular, we will extend the proposed BDN to model decisions about the possibility of joining the supply chain (based on potential risks the company would avoid or its resource availability) and the decisions about the supplier choice considering other variables such as time constraints and goodness of the agreement conditions or constraints between the suppliers at the same level of the chain.

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