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An agent-based negotiation model for supplier selection of multiple products with synergy effect

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ABSTRACT

Supplier selection is an important problem in supply chain management (SCM), and has attracted the attention of many researchers. Tremendous effort has been spent on the development of agent-based systems to automate supplier selection negotiation process in SCM applications. In this kind of multi-agent system (MAS), software agents are established to represent various parties and functions involving in the supplier selection negotiation process. Most of current systems only deal with relatively simple negotiations involving the acquisition of one product, they are not sufficient to support complex negotiations involving multiple products with synergy effect. However, in practice, it is common for a purchasing company to procure multiple products simultaneously, and the synergy effects that exist between products could affect the final choice of cooperative suppliers. This paper presents an agent-based negotiation model to automate the supplier selection process involving a bundle of products with synergy effect. A MAS is established to realize the proposed negotiation model for multi-product supplier selection. Furthermore, the negotiation proposal, negotiation protocol, negotiation strategies, and decision making methods involving in the negotiation model are elaborated for the multi-product supplier selection environment. Through the proposed negotiation model, the purchasing company and suppliers can reach agreements on the details of products simultaneously and exploit the synergy effect between products. Finally, illustrative examples are conducted to demonstrate the function and effectiveness of the negotiation model for multi-product supplier selection.

1. Introduction

Nowadays enterprises usually outsource some non-core activities and focus on core activities to reduce cost and enhance competitive capabilities (Chopra & Meindl, 2007). Then the competition between enterprises has evolved to competition between supply chains. Consequently, the performances of member enterprises determine the success of supply chain, and supplier selection becomes an important problem of supply chain management (SCM).

Supplier selection is the process of finding the suitable suppliers who can provide the buyer with the right quality products/services at the right price, in the right quantities and at the right time (De Boer, Labro, & Morlacchi, 2001). Supplier selection involves activities to solve the conflicts between the buyer and suppliers on the details of products/services. For supply chain members with conflicting interests or viewpoints, negotiation is an essential approach for decision makers to reach mutual agreements (Wang, Wong, & Wang, 2013). Supplier selection negotiations may involve a wide range of details of products/services, including price, quality, delivery time, service, and so on.

As a novel approach of business automation, agent-based systems are being increasingly used in SCM applications, involving supply chain formation (Kim & Cho, 2010), supply chain risk management (Giannakis & Louis, 2011), virtual supply chain networks (Long, 2014), etc. Regarding the features of autonomous, cooperative and pro-reactive, the agent-based systems are suitable to automate supplier selection negotiations (Kim & Cho, 2010; Wang et al., 2013; Wang, Wong, & Wang, 2012; Wong & Fang, 2010). Within an agent-based system for supplier selection negotiation, software agents are established to represent various parties and functions involving in the buyer–seller interaction process.

However, existing agent-based negotiation models for supplier selection are studied under the following two assumptions: firstly, products are negotiated one by one and cannot be negotiated simultaneously; secondly, the products are independent and the synergy effects between products are not considered. In practice,

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it is common for enterprises to procure multiple products simultaneously, synergy effect which is an effect arising between two or more items that produces an effect greater than the sum of their individual effects (Tanriverdi & Ruefli, 2004), could exist in the multi-product supplier selection environment. Furthermore, both the purchasing company and supplier can benefit from the positive synergies between products, and the synergy effect between products can affect the final choice of cooperative suppliers. For instance, it is advantageous for the purchasing company to procure products with positive synergies together to reduce cost and improve efficiency, and it is common for suppliers to supply products with positive synergies together at a lower price to increase the chance of winning bids.

Therefore, the objective of this paper is to propose an agent-based negotiation model to support multi-product supplier selection, in consideration of the synergy effect between products. Firstly, a multi-agent system (MAS) will be established to realize the proposed negotiation model. Secondly, the negotiation proposal, negotiation protocol, negotiation strategies, and decision making methods involving in the negotiation model will be elaborated for the multi-product supplier selection environment. Thirdly, through the proposed negotiation model, the purchasing company and suppliers will reach agreements on the details of products simultaneously and make full use of the synergy effect between products.

The rest of the paper is organized as follows. Section 2 reviews literature on supplier selection, and agent-based negotiation models. Section 3 introduces the agent-based negotiation model for multi-product supplier selection, in consideration of the synergy effect between products. The computational elements in the negotiation model, for instance, negotiation objects, utility functions, negotiation decision functions, winner (cooperative suppliers) determination method, and so on are proposed in Section 4. Experiments are conducted in Section 5 to demonstrate the function and effectiveness of the agent-based negotiation model for supplier selection of multiple products with synergy effect. Finally, conclusion and future work follow in Section 6.

2. Literature review

2.1. Supplier selection

Supplier selection consists of analyzing and measuring the performances of a set of suppliers on multiple selection criteria by decision making methods. The selection criteria and decision-making methods are the two main elements in supplier selection problem. The review studies on selection criteria (Weber, Current, & Benton, 1991; Wilson, 1994) pointed out that selection criteria vary according to application scenarios, and decision makers should adopt appropriate selection criteria based on their specific scenarios. However, they also presented that price, quality, delivery and service are the most frequently used selection criteria in supplier selection process. In this research, these criteria are adopted to evaluate suppliers.

Most studies on supplier selection have been focused on the decision making methods. De Boer et al. (2001) presented a review of decision methods reported in the literature for supporting supplier selection process. Ho, Xu, and Dey (2010) analyzed the decision making approaches for supplier selection based on journal articles from 2000 to 2008. Chai, Liu, and Ngai (2013) provided a systematic review on articles published form 2008 to 2012 on the application of decision making techniques for supplier selection. Researchers viewed supplier selection problem as a multi-criteria decision making (MCDM) problem that involves the trade-offs between conflicting qualitative and quantitative criteria, and pointed out that there is no common best way to evaluate and select suppliers, decision makers should adopt suitable decision making methods according to their specific scenarios.

Organizations use a variety of different approaches in their supplier selection processes. Sharma and Balan (2013) proposed an integrative approach considering Taguchi's loss function, technique for order preference by similarity to ideal solution (TOPSIS) and multi-criteria goal programming, to select relatively better performing supplier. Deng, Hu, Deng, and Mahadevan (2014) proposed a D-AHP method for the supplier selection problem based on D numbers which is a new effective and feasible representation of uncertain information. Karsak and Dursun (2014) proposed a novel fuzzy multi-criteria group decision making framework for supplier selection integrating quality function deployment and data envelopment analysis (DEA). In this research, a purchasing company can select suppliers for multiple products simultaneously and the purchasing company and suppliers can negotiate the details of products according to their preferences on products with synergy effect. Therefore, the supplier selection methods suitable for this scenario should be proposed.

The multi-product supplier selection is an emerging trend in current research. Feng, Fan, and Li (2011) proposed a decision method for selecting a pool of suppliers for the provision of different service process/product elements. Kim and Wagner (2012) addressed the supplier selection problem from the perspective of product configuration. Esmaeili Aliabadi, Kaazemi, and Pourghannad (2013) presented an integrated multi-item supplier selection model, and developed a novel two-level GA to solve the model. Kilic (2013) developed an integrated approach including fuzzy TOPSIS and a mixed integer linear programming model to select the best supplier in a multi-item/multi-supplier environment. Although these researchers proposed supplier selection for multiple products, they did not incorporate the synergy effect between products in supplier selection process. In practice, purchasing companies may express complementary or substitutable preferences over products, and the synergy effect between products could affect the final choice of cooperative suppliers. This research will propose a multi-product supplier selection model considering the synergy effect between products to fill this research gap.

2.2. Agent-based negotiation models

In the context of artificial intelligence (AI), a commonly adopted definition of agent is the notion proposed by Wooldridge and Jennings (1995): "an agent is a computer system that is situated in some environment, in which it is capable of autonomous action, in order to meet its predefined objectives". A multi-agent system (MAS) can be defined as a loosely-coupled system composed of multiple interacting agents that work collectively through cooperation or competition to solve problems that would be beyond their individual capabilities (O'Hare and Jennings, 1996). In the MAS domain, negotiation has been perceived as the most fundamental and powerful mechanism for managing inter-agent dependencies at runtime (Jennings et al., 2001). Through negotiation, a group of agents could reach mutually acceptable agreements on some matters.

For a supply chain, it is practical for the purchasing company and suppliers to negotiate on the details of products. A series of studies were conducted to automate supplier selection negotiation through the agent-based negotiation models. Cakravastia and Takahashi (2004) proposed a multi-objective model to support the process of supplier selection and negotiation that considers the effect of these decisions on the manufacturing plan. Kim and Cho (2010) used agent negotiation as a way to allocate numerous orders to many participants for supply chain formation. Wong and Fang (2010) presented ECNPro (the Extended Contract-Netlike multilateral Protocol), which is a new multi-agent protocol for handling buyer–seller negotiations in SCM. Huang, Liang, Lai, and Lin (2010) presented a multiple attributes negotiation model for B2C e-commerce, which deploys intelligent agents to facilitate autonomous and automatic on-line buying and selling by intelligent agents while quickly responding to consumers. Wang et al. (2012) established a MAS platform for individual companies to form an ecological virtual enterprise based on ontology theory and intelligent agents. In these agent-based negotiation models, the supplier selection process is abstracted as a buyer–seller relationship, and the MCDM approaches are used in the decision making process of agents to evaluate suppliers. However, most of existing negotiation models support supplier selection for a single product or product-by-product, while do not support supplier selection for multiple products simultaneously, let alone consider the synergy effect between products.

Generally speaking, three areas should be considered in the negotiation scheme (Faratin, Sierra, & Jennings, 1998): negotiation objects confining the range of issues over which agreement must be reached, negotiation protocols regulating the set of rules that govern the interaction, and agents' decision making models directing agents' moves towards a negotiation solution. For researches on agent-based automated negotiation scheme, the negotiation protocols (Wang, Wong, & Wang, 2014; Wong & Fang, 2010) and agent decision-making models (Lee & Ou-Yang, 2009; Ren & Zhang, 2014; Talluri, 2002; Wang, Wong, & Wang, 2011) are the major focusing issues. However, existing negotiation protocols and agent decision-making models are not suitable for the multi-product supplier selection environment. In this research, negotiation scheme suitable for the multi-product supplier selection environment should be extended.

3. Agent-based negotiation model for multi-product supplier selection

The objective of the agent-based negotiation model is to support the negotiation between the purchasing company and suppliers on multiple products simultaneously, in consideration of the synergy effect between products. As it involves one buyer (purchasing company) and many suppliers, the agent-based negotiation model is therefore a one-to-many multi-issue negotiation model. To cater for the multi-product environment, the agent-based negotiation model is extended to support negotiation on multiple products with synergy effect. The basic functions of the agent-based negotiation model for multi-product supplier selection are implemented in JADE (Java Agent Development Framework) platform (Bellifemine, Caire, & Greenwood, 2007).

In view of the synergy effects that exist between products, the buyer would tend to procure together the bundle of products with positive synergies. The term "product bundle" is adopted to represent the product combination that the purchasing company prefers to procure together. In the negotiation process, the product bundles can represent the purchasing company's preferences on products, and control the types of bids that suppliers are allowed to submit. Suppliers can elicit the purchasing company's preferences on products based on the types of allowed product bundles, and submit different bids for the allowed product bundles to improve the chance of winning bids.

3.1. MAS architecture of the negotiation model for multi-product supplier selection

A MAS is established to implement the negotiation model to support the multi-lateral multi-issue negotiation on multiple products with synergy effect. The MAS comprises software agents representing various parties and functions involving in the buyer–seller negotiation process. As shown in Fig. 1, five types of agents, namely, the TDA (Task Decomposer Agent), the CA (Coordinator Agent), the SDA (Synergy Determination Agent), the BA (Buyer Agent), and the SA (Seller Agent) are involved. The respective functions of the agents are as follows.

- TDA (Task Decomposer Agent)
  - Determine the set of required products.
- CA (Coordinator Agent)
  - Control the interactions of agents involving the negotiation model.
  - Create instances of the BAs for all the suppliers (SAs).
  - Configure negotiation strategies of the BAs for different suppliers and different product bundles.
  - Control the multi-bilateral bargaining between the BAs and the SAs.
  - Select cooperative suppliers for products based on the negotiation results between the BAs and the SAs.
- SDA (Synergy Determination Agent)
  - Generate the preferred product bundles according to the purchasing company's preferences on products.
- BA (Buyer Agent)
  - Represent the purchasing company and conduct the bilateral bargaining with the corresponding SA.
- SA (Seller Agent)
  - Represent supplier and conduct the bilateral bargaining with the corresponding BA.

3.2. Procedure of the negotiation model for multi-product supplier selection

As shown in Fig. 2, the negotiation model for multi-product supplier selection is composed of three phases: preparation, multi-bilateral bargaining and winner (cooperative suppliers) determination. The functions of the three phases are explained as follows.

3.2.1. Preparation phase

The functions of the preparation phase include: to determine the preferred product bundles based on the purchasing company's preferences on products; to create instances of the BA for all the suppliers (SAs); and to configure the negotiation strategies for the BAs. A product bundle determination algorithm (Yu & Wong, 2013) has been established and implemented for generating the preferred product bundles that the purchasing company prefers to procure together.

3.2.2. Multi-bilateral bargaining phase

The function of this phase is to support the multiple bilateral bargaining between the BAs and the SAs, and to obtain the final bids of suppliers for products. During the bargaining process, the BAs and SAs exchange proposals to bargain over a bundle of products. Each proposal comprises a set of bids for products. Within the allowable negotiation time (i.e. negotiation deadline is not reached), the agent can evaluate the proposal/counter-proposal proposed by the opponent bid-by-bid. According to the negotiation decision functions (details presented in Section 4.3), the agent can accept the bid, or reject the bid and generate a counter-bid. In each negotiation round, if a counter-bid exists, the agent proposes a counter-proposal composed of counter-bids to its opponent; otherwise, the agent accepts the proposal with multiple bids. The BA and the SA conduct the bargaining behaviors in a similar way.

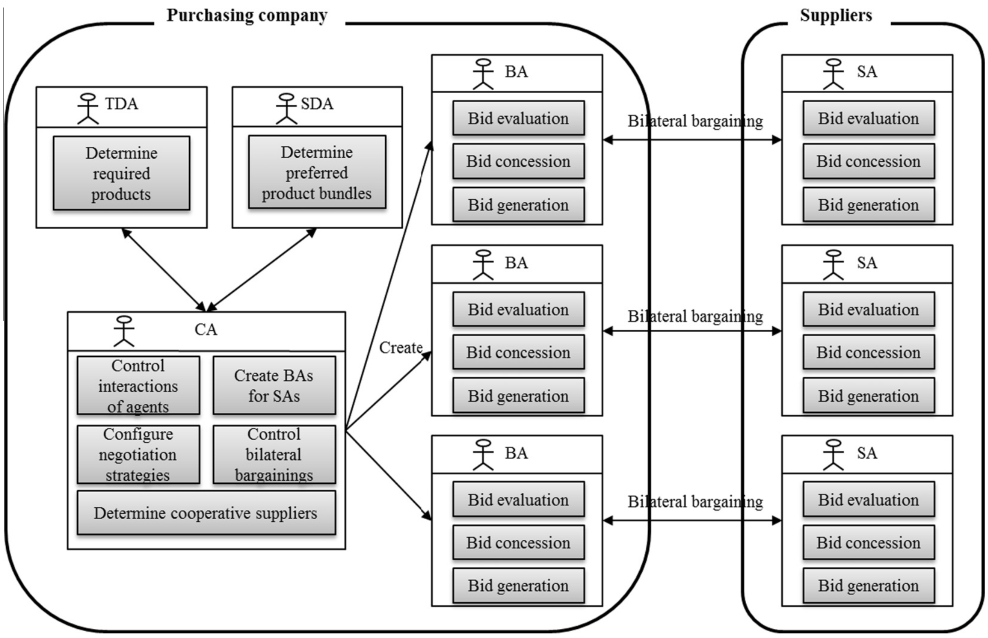

Fig. 1. MAS architecture of the negotiation model for multi-product supplier selection.

3.2.3. Winner determination phase

After receiving the bargaining results from the multi-bilateral bargaining phase, the winner determination phase is conducted to select the cooperative suppliers based on the final bids submitted by suppliers. A branch-and-band (B&B) based winner determination algorithm is adopted to determine the cooperation suppliers based on these final negotiated bids.

3.3. Negotiation protocol of the negotiation model for multi-product supplier selection

The negotiation protocol governing the interaction of agents involving in the negotiation model for multi-product supplier selection is a hybrid protocol of combinatorial procurement auction and multi-bilateral bargaining. The combinatorial procurement auction protocol is responsible for initiating the multi-bilateral bargaining between the BAs and the SAs, obtaining final bids from the SAs, and determining the cooperative suppliers for products based on the final bids. The multi-bilateral bargaining protocol supports the multiple one-to-one negotiations between the BA and the SA. Corresponding to the procedure of the negotiation model for multi-product supplier selection, the combinatorial procurement auction protocol supports the preparation phase and the winner determination phase, and the multi-bilateral bargaining protocol governs the multi-bilateral bargaining phase.

The alternating-offer protocol is adopted to support the multi-round bilateral bargaining between the BAs and the SAs. This protocol can be implemented by the FIPA Request Protocol and the FIPA Iterated CNP. In the multi-bilateral bargaining protocol, to submit different commitments for different product bundles concurrently, multiple bids are conveyed as a package deal, and multiple commitments are included in each bid. Here, the set of bids proposed by the seller side is called a proposal, while a package of bids proposed by the buyer side is called a counter-proposal. A negotiation round involves one proposal and one counter-proposal. In each negotiation round, the BA and the SA can either make

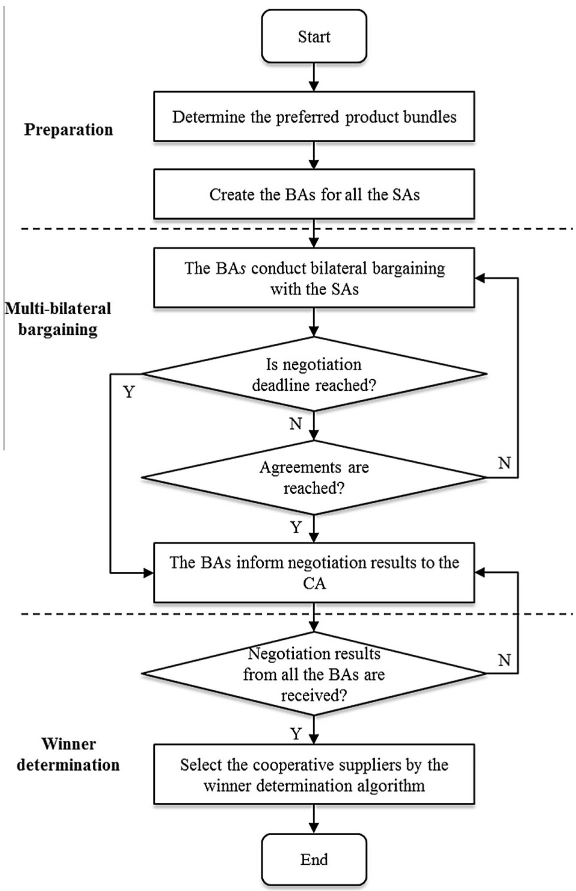

Fig. 2. Procedure of the negotiation model for multi-product supplier selection.

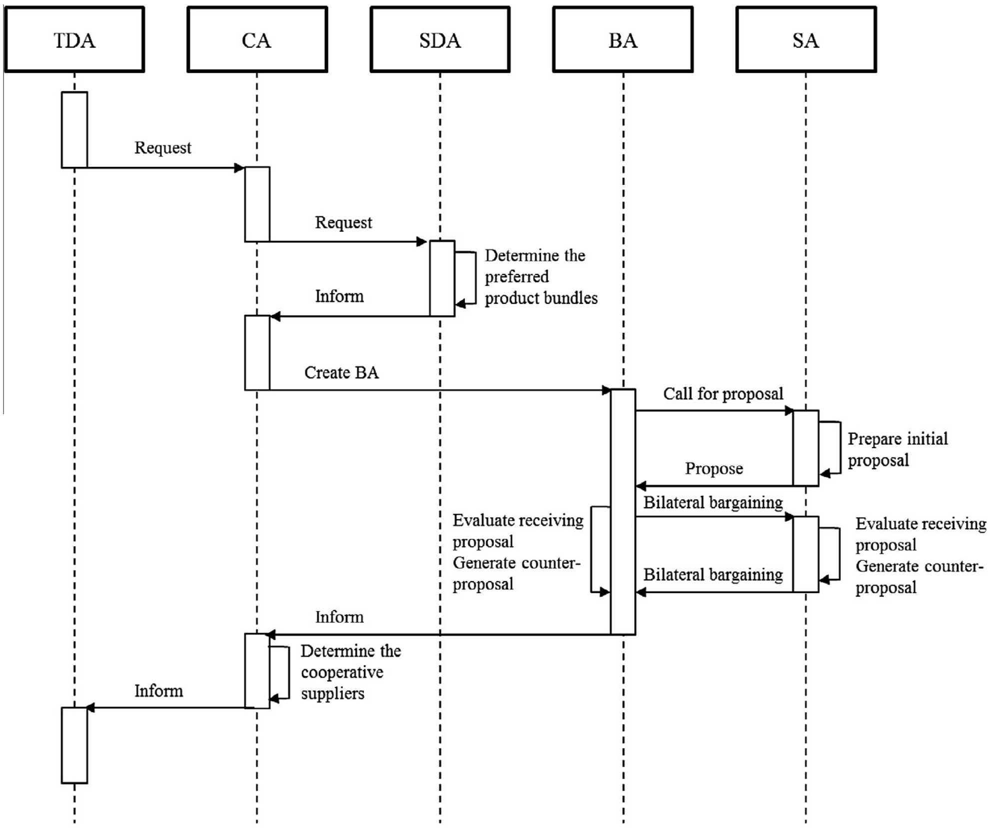

Fig. 3. Protocol of the negotiation model for multi-product supplier selection.

concessions or stick to their previous issue values. The alternate and iterated placements of proposals and counter-proposals by the SA and the BA form a bilateral bargaining process, which is also a sequence of negotiation rounds. The proposed negotiation model is composed of one or more bilateral bargaining process in accordance with the number of BA instances and the SA counterparts. Fig. 3 shows the interactions of agents according to the proposed negotiation protocol.

4. Computational elements in the negotiation model for multi-product supplier selection

The negotiation model mainly deals with the supplier selection for multiple products by delivering the negotiation issues and concession routes as numerical values. It requires that all the relevant negotiation knowledge such as negotiation objects, evaluation functions, negotiation decision functions, and winner determination method should be expressed in a computable manner. The notations used in the negotiation model are depicted in Table 1.

4.1. Negotiation object

4.1.1. Negotiation issue

Multiple criteria are involved to evaluate the bids submitted by suppliers. In the proposed negotiation model the negotiation issues are price, quality, delivery and service, and they are selection criteria to evaluate suppliers. In order to facilitate the expression of the decision-maker's preferences under a multi-criteria perspective,

Table 1
Notations of the negotiation model for multi-product supplier selection.

Notations	Illustrations
$\{b,s\}$	Buyer agent, seller agent
$P = \{P_1,\ldots,P_i,\ldots,P_M\}$	A set of products
$D = \{d_1,\ldots,d_i,\ldots,d_M\}$	The demand of products
$PB = (p_1,\ldots,p_i,\ldots,p_M)$	A product bundle, if the i-th product is in the PB, $p_i = 1$; otherwise, $p_i = 0$
$Q = (q_1,\ldots,q_i,\ldots,q_M)$	Quantities of products
I_k	The value of the kth negotiation issue
$Bid = \langle PB, I_1,\ldots,I_k,\ldots,I_K, Q\rangle$	A bid submitted by supplier
$Pro = \{Bid_1, Bid_2,\ldots\}$	A proposal submitted by supplier
$CPro = \{Bid_1, Bid_2,\ldots\}$	A counter proposal submitted by purchasing company
$V^k_{\min}$	The minimum utility of the k-th negotiation issue
β	The risk preference of the decision maker, $0 < \beta < 1$, risk prone; $\beta = 1$, risk neutral; $\beta > 1$, risk averse
$V(I_k)$	The utility function for quantitative negotiation issue I_k
$V(\tilde{I}_k)$	The utility function for the qualitative negotiation issue $\tilde{I}_k$
ω_k	The weight of the kth negotiation issue
$U(Bid)$	The utility function for bid Bid
b_k	Discount rate of the kth negotiation issue of buyer agent b
γ	Concession preference of the decision maker, $0 < r < 1$, acceleration; $\gamma = 1$, constant; $\gamma > 1$, deceleration
$\alpha^b_k(t)$	Concession rate of buyer agent b, the kth negotiation issue at time t
$U^b_{\min}$	Reservation utility value of the buyer agent

the issues can be expressed in either quantitative or qualitative form. Thus, price and delivery are quantitative issues; quality and service are qualitative issues.

4.1.2. Negotiation bid

In the proposed negotiation model, a bid is composed of the product bundle identification and the corresponding details of products. To illustrate, for a negotiation model involving the procurement of M products with K negotiation issues, the bid is a vector $Bid = \langle PB, I_1, \ldots, I_k, \ldots, I_K, Q\rangle$, where PB is the product bundle identification denoted by $PB = (p_1, \ldots, p_i, \ldots, p_M)$. When the ith product is included in the bid, $p_i = 1$, otherwise $p_i = 0$. I_k is the value of the kth negotiation issue. Q is the quantities of products in the product bundle denoted by $Q = (q_1, \ldots, q_i, \ldots, q_M)$, if $p_i = 1$, q_i is quantity of the ith product, otherwise $q_i = 0$.

For instance, if 3 products are to be acquired and the negotiation issues adopted in the negotiation model are price, quality, delivery and service, that is, $M = 3$ and $K = 4$. The purchasing company wants to buy a set of products $P = \{P_1, P_2, P_3\}$. A supplier submits a bid $\langle(110), 500$, *very good*, 4, *medium*, $(1000, 800, 0)\rangle$, and it means that the supplier provide products P_1 and P_2 together with a bundle price 500, which is usually smaller than the price sum of just supplying P_1 or P_2, *very good* quality, 4 days delivery, *medium* service, and 1000 unit P_1 and 800 unit P_2.

4.1.3. Negotiation proposal and counter-proposal

To cater for the multi-product supplier selection environment, the negotiation model adopted in this paper is extended for multi-product and to incorporate the synergy effect between products. In the negotiation model, suppliers are allowed to submit proposal and counter-proposal with multiple bids for different product bundles to improve the chance of winning bids. For instance, supplier $S1$ submits a proposal with three bids $Pro = \{Bid_1, Bid_2, Bid_3\}$ to represent its different commitments on the three types of product bundles. These proposals, comprising multiple bids from suppliers, are encoded in XML (Extensible Markup Language) in the ACL messages. Fig. 4 shows a proposal example submitted by supplier $S1$ which is composed of three bids.

```
<?xml version="1.0" encoding="UTF-8"?>
<Proposal>
    <Bid Id="01" >
        <ProductBundle>100</ProductBundle>
        <Price>650</Price>
        <Quality>M</Quality>
        <Delivery>20</Delivery>
        <Service>P</Service>
        <Quantity>1000,0,0</Quantity>
        <Submitter>S1</Submitter>
    </Bid>
    <Bid Id="02" >
        <ProductBundle>010</ProductBundle>
        <Price>850</Price>
        <Quality>VP</Quality>
        <Delivery>30</Delivery>
        <Service>G</Service>
        <Quantity>0,1000,0</Quantity>
        <Submitter>S1</Submitter>
    </Bid>
    <Bid Id="03" >
        <ProductBundle>110</ProductBundle>
        <Price>1500</Price>
        <Quality>VG</Quality>
        <Delivery>25</Delivery>
        <Service>M</Service>
        <Quantity>1000,1000,0</Quantity>
        <Submitter>S1</Submitter>
    </Bid>
</Proposal>
```

Fig. 4. Proposal example submitted by supplier $S1$.

4.2. Evaluation function

In the negotiation model, the proposal/counter-proposal should be evaluated bid-by-bid to decide the acceptability. Since multiple negotiation issues are involved in a bid, the evaluation function falls into the domain of multi-attribute decision making. Accordingly, the multi-attribute utility theory (MAUT) method is employed as the foundation of the evaluation function (Edwards, 1992).

4.2.1. Negotiation issues normalization

Based on MAUT, the primary concern is to normalize the value on each negotiation issue into a 0–1 scale. The quantitative issue can be decomposed into benefit issues and cost issues. For a benefit issue, the larger the issue value is the better; for a cost issue, the smaller the issue value is the better. Since numerical values can be assigned to quantitative issues, normalized utility of quantitative issues can be computed straightforwardly. However, the MAUT only considers the linear utility function which means the decision maker should be risk neutral. In order to make the evaluation function more comprehensive to reflect other risk preferences, nonlinear utility functions are also included. Eqs. (1) and (2) show the expressions of utility functions for quantitative issues:

When $0 < \beta \leqslant 1$, polynomial

$$V(I_k) = \begin{cases} V^k_{\min} + (1 - V^k_{\min}) \times \left(\frac{I_k - \min_k}{\max_k - \min_k}\right)^{1/\beta} & \text{Benefit} \\ V^k_{\min} + (1 - V^k_{\min}) \times \left(\frac{\max_k - I_k}{\max_k - \min_k}\right)^{1/\beta} & \text{Cost} \end{cases} \tag{1}$$

When $\beta > 1$, exponential

$$V(I_k) = \begin{cases} \exp\left(\left(1 - \frac{I_k - \min_k}{\max_k - \min_k}\right)^{\beta} \ln V^k_{\min}\right) & \text{Benefit} \\ \exp\left(\left(1 - \frac{\max_k - I_k}{\max_k - \min_k}\right)^{\beta} \ln V^k_{\min}\right) & \text{Cost} \end{cases} \tag{2}$$

In Eqs. (1) and (2), $V^k_{\min}$ is the minimum utility determined by the decision maker for the kth negotiation issue. β is a positive real number which can reflect the risk preference level of the decision maker. When $\beta < 1$, the polynomial utility function is chosen and the decision maker has the attitude of risk prone. When $\beta = 1$, also the polynomial utility function is chosen, and the decision maker has the attitude of risk neutral. When $\beta > 1$, the exponential utility function is chosen and the decision maker has the attitude of risk averse. That means, the smaller the β value is, the more prone the decision maker prefers to risk the losing of negotiation convergence to achieve higher utility. The purchasing company and suppliers can simulate different risk preference levels on the

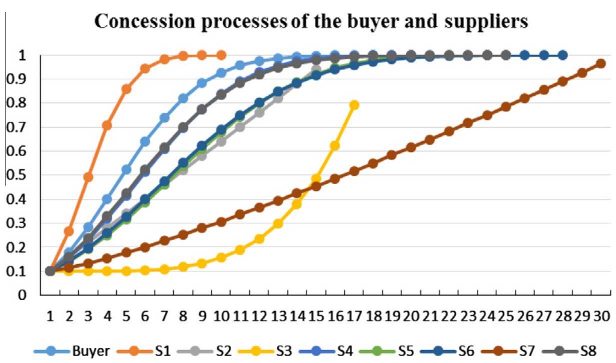

Fig. 5. Concession process of the purchasing company and suppliers.

negotiation process by adjusting the parameter β in Eqs. (1) and (2). For instance, if the required products are urgent, and the purchasing company worry that the trading is not successful, the purchasing company can assign a bigger value to the parameter β. Otherwise, the purchasing company can strive for better utility at the risk of unsuccessful trading by assigning a smaller value to the parameter β.

Qualitative issues are descriptive in nature and not straightforward to be expressed in numerical values. To avoid assigning crisp values that might not adequately reflect their perspectives, the decision makers are asked to rate the issues using linguistic expressions. Subsequently, the related numeric values in 0–1 scale can be obtained by fuzzy methods (Mikhailov, 2002). Let triangular fuzzy number (TFN) $\tilde{I}_k = (m_1, m_2, m_3)$ represents the qualitative issue. The TFNs can be transformed into 0–1 scale based on the graded mean integration representation method as shown in Eq. (3) (Chou, 2003). The use of linguistic expressions and fuzzy method is advantageous as a crisp assignment of issues that is not desirable is avoided, so that human thoughts can be represented easily and intuitively:

$$V(\tilde{I}_k) = \frac{1}{6}(m_1 + 4m_2 + m_3), \quad k = 1, 2, \ldots, K \tag{3}$$

4.2.2. Bid utility function

The aggregated utility of a bid is calculated as the weighted sum of all the negotiation issues the same as in the MAUT method. To calculate the weighted sum, each negotiation issue should be assigned a weight ω_k. The decision maker can represent their actual needs on the detailed commitments of products by adjusting the weights. In such case, the assignment of weights can be based on experience (heuristic) or a specific preference of the decision maker. In the negotiation model, the bid submitted by suppliers can be evaluated by Eq. (4):

$$U(Bid) = \sum_k \omega_k V(I_k)\left(\sum_k \omega_k = 1\right), \quad k = 1, 2, \ldots, K \tag{4}$$

It is straightforward to determine the value spaces for quantitative issues; generally, the value space is bounded between the minimum and maximum affordable values. In the multi-product supplier selection environment, the decision maker's preferences on multiple products with synergy effect can be represented by assigning different $[\min_k, \max_k]$ for different product bundles. For instance, a purchasing company procures products P_1 and P_2 simultaneously, and the value space of delivery issue $[\min_{delivery}, \max_{delivery}]$ for product P_1 is [1,7] and for product P_2 is [1,14]. If the purchasing company prefers to procure products P_1 and P_2 together, the purchasing company can relax the value space of delivery issue as [1,20]. By assigning different $[\min_k, \max_k]$ for different product bundles, utilities for the same negotiation issue value could be different for bids with different product bundles. As the utility of bid is based on the utility of negotiation issues, the proposed bid utility function also can reflect the decision maker's preferences on products with synergy effect. The purchasing company and suppliers can simulate different preferences on products by adjusting the parameters $\min_k$ and $\max_k$ in Eqs. (1) and (2).

4.3. Negotiation decision function

4.3.1. Concession function and generation function

When the negotiation opponent's proposal/counter-proposal cannot be accepted, the buyer agent or seller agent can choose to generate a new counter-proposal or proposal by conceding on one or more negotiation issues. Concessions made are calculated based on some concession tactics. The concession tactics involving time-dependent, resource-dependent and behavior-dependent tactics introduced by Faratin et al. (1998) are applicable computational approaches for the composition of negotiation strategies reflecting agents' attitudes towards risks, time limits and resource availability. Due to its tractability for applications, the time-dependent concession is frequently adopted in negotiation decision function to control how much to concede for multiple issues in each round (Faratin et al., 1998).

For the time-dependent concession tactic, time is the predominant factor used to decide how to make concession. The concession rate is a variable depending on time or the number of negotiation rounds. In the tth ($t = 1,2,3,\ldots$) negotiation round, buyer agent b's concession rate for issue I_k can be defined as Eq. (5):

$$\alpha_k^b(t) = \begin{cases} b_k + (1 - b_k)((t-1)/t_{\max})^{1/\gamma} & (0 < \gamma \leqslant 1) \\ \exp\left((1 - (t-1)/t_{\max})^{\gamma} \ln b_k\right) & (\gamma > 1) \end{cases} \tag{5}$$

Based on this concession rate, the value of issue I_k of counter-bid in the tth ($t = 1,2,3,\ldots$) negotiation round can be expressed as Eq. (6):

$$I_k^b(t) = \begin{cases} \min_k + \alpha_k^b(t)(\max_k - \min_k) & \text{Cost} \\ \max_k - \alpha_k^b(t)(\max_k - \min_k) & \text{Benefit} \end{cases} \tag{6}$$

In Eq. (5), $t_{\max}$ is the maximum willing concession step, $\max_k$ and $\min_k$ are the upper and lower value bounds of issue I_k. They can also be perceived as the reservation and aspiration issue values which are respectively the least and best acceptable values. In the concession function, b_k reflects the discount rate. The variable γ determines the acceleration or deceleration of the concession. When $0 < \gamma < 1$, concessions are made with increasing speed, that means, the concession speed is low in the initial stage, and then increases gradually. When $\gamma = 1$, concessions are made in a constant speed. When $\gamma > 1$, concessions are made with decreasing speeds, that means, the concession speed is high in the initial stage, and then decreases gradually to a small value. It can be suggested that, the smaller the γ value is, the more patient an agent performs in the concession. As the decision making function and bid generation function are based on the concession rate, the agents can adopt different negotiation strategies by adopting different conceding strategies. For the time-dependent conceding strategy in this paper, the purchasing company and suppliers can simulate different negotiation strategies by adjusting the parameter γ in Eq. (5).

4.3.2. Responding function

In negotiation round t, if $t < t_{\max}$, where $t_{\max}$ is the maximum negotiation round (deadline), the agent evaluate the proposal/counter-proposal proposed by the opponent bid-by-bid. A bid can be acceptable to the buyer agent when two conditions are satisfied as shown in Eq. (7), referring to the negotiation decision function introduced in Faratin et al. (1998); otherwise the buyer agent rejects it and generates a counter-bid. If a counter-bid exists, the buyer agent proposes a counter-proposal composed of counter-bids to its opponent; otherwise, the buyer agent accepts the proposal with multiple bids. $U_{\min}^b$ is the reservation utility value of the buyer agent. It means that the utility value of the seller agent's current bid should not be less than the reservation utility value of the buyer agent, as well as the utility value of the counter-bid to be proposed by the buyer agent. For the seller agent, the structures of the evaluation function and acceptability condition are the same as those for the buyer agent:

$$\begin{cases} U(Bid_s^t) \geqslant U_{\min}^b \\ U(Bid_s^t) \geqslant U\left(Bid_b^{t+1}\right) \end{cases} \tag{7}$$

Table 2
The requirements of required products.

Product id	Product type	Requirements				
		Model number	Material	Delivery	Warranty	Quantity
P_1	Camshaft	M-01	Steel	⩽20 days	⩾1 year	1000 unit
P_2	Crankshaft	M-01	Steel	⩽20 days	⩾1 year	1000 unit
P_3	Cylinder block	M-01	Aluminum	⩽30 days	⩾1 year	2000 unit
P_4	Cylinder head	M-01	Aluminum	⩽30 days	⩾1 year	2000 unit

Table 3
Value spaces and relative weights for negotiation issues of purchasing company.

Product bundle	Price	Quality	Delivery	Service
1000	[50,60]	{VP,P,M,G,VG}	[1,10]	{VP,P,M,G,VG}
0100	[70,80]	{VP,P,M,G,VG}	[1,20]	{VP,P,M,G,VG}
0010	[90,100]	{VP,P,M,G,VG}	[1,30]	{VP,P,M,G,VG}
0001	[110,120]	{VP,P,M,G,VG}	[1,20]	{VP,P,M,G,VG}
1100	[120,145]	{VP,P,M,G,VG}	[1,20]	{VP,P,M,G,VG}
1010	[140,165]	{VP,P,M,G,VG}	[1,30]	{VP,P,M,G,VG}
1001	[160,185]	{VP,P,M,G,VG}	[1,20]	{VP,P,M,G,VG}
0110	[160,185]	{VP,P,M,G,VG}	[1,30]	{VP,P,M,G,VG}
0101	[180,205]	{VP,P,M,G,VG}	[1,20]	{VP,P,M,G,VG}
0011	[200,225]	{VP,P,M,G,VG}	[1,30]	{VP,P,M,G,VG}
Weight	0.4	0.3	0.15	0.15

For instance, at negotiation round t, the buyer agent b receives a proposal with three bids $\{Bid_1, Bid_2, Bid_3\}$ for product bundles 100, 011, and 110 respectively, and the utilities for the three bids are 0.82, 0.78, and 0.75. By comparing with the reservation utility $U^b_{\min} = 0.1$ and $U\left(Bid^{t+1}_{b1}\right) = U\left(Bid^{t+1}_{b2}\right) = U\left(Bid^{t+1}_{b2}\right) = 0.80$, b accepts Bid_1, rejects Bid_2 and Bid_3 and generates counter-bids for Bid_2 and Bid_3. As counter-bids exist, b proposes a counter-proposal with counter-bids to its opponent seller agent.

4.4. Winner determination of the negotiation model for multi-product supplier selection

In the winner determination phase of the proposed negotiation model, the selection of cooperative suppliers based on the final bids submitted by suppliers can be formulated as a WDP (winner determination problem) as a traditional combinatorial procurement auction. In this case, the purchasing company is the auctioneer, and suppliers are bidders. Based on the final bids proposed by suppliers, the objective of the purchasing company is to select the optimal combination of bids to maximize its utility, under the constraints that all the demands of products are satisfied, and no more than one bid is selected from a single bidder. The cooperative suppliers are bidders submitting the selected bids. The WDP of the negotiation model for multi-product supplier selection can be formulated as the following IP (integer programming) problem:

$$\max \sum_{j \in N} U(Bid_j) y_j \tag{8}$$

Table 4
Value spaces and relative weights for negotiation issues of suppliers.

Supplier	Product bundle	Price	Quality	Delivery	Service
S1	1000	[55,65]	{VP,P,M,G,VG}	[5,20]	{VP,P,M,G,VG}
	0100	[75,85]	{VP,P,M,G,VG}	[10,30]	{VP,P,M,G,VG}
	1100	[125,150]	{VP,P,M,G,VG}	[5,25]	{VP,P,M,G,VG}
	Weight	0.4	0.3	0.15	0.15
S2	1000	[56,66]	{VP,P,M,G,VG}	[4,20]	{VP,P,M,G,VG}
	0010	[94,104]	{VP,P,M,G,VG}	[15,40]	{VP,P,M,G,VG}
	1010	[145,170]	{VP,P,M,G,VG}	[10,30]	{VP,P,M,G,VG}
	Weight	0.3	0.4	0.15	0.15
S3	1000	[54,64]	{VP,P,M,G,VG}	[6,25]	{VP,P,M,G,VG}
	0001	[116,126]	{VP,P,M,G,VG}	[10,30]	{VP,P,M,G,VG}
	1001	[165,190]	{VP,P,M,G,VG}	[10,25]	{VP,P,M,G,VG}
	Weight	0.3	0.3	0.2	0.2
S4	0100	[75,85]	{VP,P,M,G,VG}	[15,40]	{VP,P,M,G,VG}
	0010	[95,105]	{VP,P,M,G,VG}	[10,30]	{VP,P,M,G,VG}
	0110	[165,190]	{VP,P,M,G,VG}	[10,30]	{VP,P,M,G,VG}
	Weight	0.4	0.2	0.2	0.2
S5	0100	[76,86]	{VP,P,M,G,VG}	[10,20]	{VP,P,M,G,VG}
	0001	[114,124]	{VP,P,M,G,VG}	[15,25]	{VP,P,M,G,VG}
	0101	[185,210]	{VP,P,M,G,VG}	[10,20]	{VP,P,M,G,VG}
	Weight	0.3	0.4	0.15	0.15
S6	0010	[96,106]	{VP,P,M,G,VG}	[5,15]	{VP,P,M,G,VG}
	0001	[115,125]	{VP,P,M,G,VG}	[10,20]	{VP,P,M,G,VG}
	0011	[206,231]	{VP,P,M,G,VG}	[5,15]	{VP,P,M,G,VG}
	Weight	0.3	0.3	0.2	0.2
S7	0100	[74,84]	{VP,P,M,G,VG}	[5,15]	{VP,P,M,G,VG}
	0001	[114,124]	{VP,P,M,G,VG}	[6,18]	{VP,P,M,G,VG}
	Weight	0.4	0.2	0.2	0.2
S8	0010	[94,104]	{VP,P,M,G,VG}	[4,20]	{VP,P,M,G,VG}
	0001	[115,125]	{VP,P,M,G,VG}	[6,15]	{VP,P,M,G,VG}
	Weight	0.4	0.4	0.1	0.1

Table 5
TFNs for qualitative issues.

Linguistic variables	Abbreviation	TFNs of purchasing company	TFNs of supplier
Very good	VG	(0.75,1,1)	(0,0,0.25)
Good	G	(0.5,0.75,1)	(0,0.25,0.5)
Medium	M	(0.25,0.5,0.75)	(0.25,0.5,0.75)
Poor	P	(0,0.25,0.5)	(0.5,0.75,1)
Very poor	VP	(0,0,0.25)	(0.75,1,1)

Table 6
Configuration of parameters in negotiation process.

Agent	Risk preference (β)	Deadline	Discount rate	Concession preference (γ)
BA	4.2	20	0.1	5.7
*S*1	3	10	0.1	5.3
*S*2	1	15	0.1	1
*S*3	0.67	17	0.1	0.23
*S*4	1.5	20	0.1	4.3
*S*5	2.5	24	0.1	3.8
*S*6	2	28	0.1	4.7
*S*7	0.4	30	0.1	0.82
*S*8	3.5	25	0.1	5.7

Table 7
Initial bids submitted by suppliers (Experiment 1).

Bid Id	Product bundle	Price	Quality	Delivery	Service	Quantity	Supplier
1	1000	650	VP	20	VP	1000,0,0,0	*S*1
2	0100	850	VP	30	VP	0,1000,0,0	*S*1
3	1100	1500	VP	25	VP	1000,1000,0,0	*S*1
4	1000	660	VP	20	VP	1000,0,0,0	*S*2
5	0010	1040	VP	40	VP	0,0,2000,0	*S*2
6	1010	1700	VP	30	VP	1000,0,2000,0	*S*2
7	1000	640	VP	25	VP	1000,0,0,0	*S*3
8	0001	1260	VP	30	VP	0,0,0,2000	*S*3
9	1001	1900	VP	25	VP	1000,0,0,2000	*S*3
10	0100	850	VP	40	VP	0,1000,0,0	*S*4
11	0010	1050	VP	30	VP	0,0,2000,0	*S*4
12	0110	1900	VP	30	VP	0,1000,2000,0	*S*4
13	0100	860	VP	20	VP	0,1000,0,0	*S*5
14	0001	1240	VP	25	VP	0,0,0,2000	*S*5
15	0101	2100	VP	20	VP	0,1000,0,2000	*S*5
16	0010	1060	VP	15	VP	0,0,2000,0	*S*6
17	0001	1250	VP	20	VP	0,0,0,2000	*S*6
18	0011	2310	VP	15	VP	0,0,2000,2000	*S*6
19	0100	840	VP	15	VP	0,1000,0,0	*S*7
20	0001	1240	VP	18	VP	0,0,0,2000	*S*7
21	1000	1040	VP	20	VP	1000,0,0,0	*S*8
22	0100	1250	VP	15	VP	0,1000,0,0	*S*8

Subject to

$$\sum_{j \in N} q_{ji} y_j \geqslant d_i, \quad i \in M \tag{9}$$

$$\sum_{PB \subset P} y_j \leqslant 1, \quad \forall j \in N \tag{10}$$

$$y_j = \{0, 1\}, \quad \forall j \in N \tag{11}$$

In the objective function (8), $U(Bid_j)$ is the bid utility function of the jth final bid, and N is the number of final bids. The constraint (9) ensures that the demands of all the required products are satisfied. The constraint (10) which ensures that no more than one bid is selected from a single bidder, can stimulate suppliers to submit more attracting bids. The variable y_j is equal to 1 if and only if the bid Bid_j is selected; otherwise the variable y_j is equal to 0. The B&B (branch-and-bound) algorithm is a general algorithm for finding optimal solutions of various optimization problems, especially in IP problems (Sandholm, 2002). Since the number of required products and the types of preferred product bundles can be controlled, the complexity of the WDP is controlled, a B&B-based winner determination algorithm branching-on-bids is adopted to solve the WDP of the proposed negotiation model.

5. Simulation and experimental results

A simulation is conducted to demonstrate the function and effectiveness of the agent-based negotiation model for supplier selection of multiple products with synergy effect. The simulation is conducted in the scenario that an automobile manufacturer A needs to procure a set of engine parts {*camshaft, crankshaft, cylinder block, cylinder head*}, and eight auto parts and components manufacturers are interested in the trading. In this case, the automobile manufacturer A is the purchasing company and the auto parts and components manufacturers are suppliers. The requirements of required products are shown in Table 2. In the simulation, the set of required products are denoted by $\{P_1, P_2, P_3, P_4\}$, and suppliers are represented by {*S*1, *S*2, *S*3, *S*4, *S*5, *S*6, *S*7, *S*8}. As multiple bids are submitted by suppliers, the purchasing company declares that no more than one bid is selected from a single supplier to stimulate the competition between suppliers. The purchasing company also declares that suppliers are allowed to place product bundles with no more than two products to control the complexity of supplier selection problem.

The supplier selection criteria adopted in this simulation, i.e., the negotiation issues are {*price*, *quality*, *delivery*, *service*} corresponding to $\{I_1, I_2, I_3, I_4\}$ respectively. The settings of negotiation issue value spaces and relative weights of the purchasing company and suppliers are assigned by decision makers as shown in Tables 3 and 4 according to their preferences on products. Linguistic values {*Very poor, Poor, Medium, Good, Very good*} are defined to represent decision makers' performances on qualitative issues *quality* and *service*, and the corresponding TFNs for the purchasing company and suppliers are listed in Table 5. Table 6 shows the configuration of parameters used in negotiation process. As the purchasing company is eager to buy these products, the BA has been assigned a high risk preference value (i.e. $\beta > 1$) to reflect its attitude on the negotiation convergence. Here, $\beta = 4.2$ for the BA, and different β values are assigned to different SAs to represent their different attitudes on the negotiation convergence. Similarly, different concession preferences γ are assigned to the BA and SAs to simulate their respective concession behaviors.

5.1. Experiment 1: function of the negotiation model for multi-product supplier selection

Agents involving in the negotiation model are the TDA, CA, SDA, *BA*1, *BA*2, *BA*3, *BA*4, *BA*5, *BA*6, *BA*7, *BA*8, *S*1, *S*2, *S*3, *S*4, *S*5, *S*6, *S*7, and *S*8. The implementation procedure of the negotiation model for multi-product supplier selection is summarized as follows:

- Step 1: The TDA sends supplier selection request for products $\{P_1, P_2, P_3, P_4\}$ as shown in Table 2 to the CA.
- Step 2: The CA receives the supplier selection request from the TDA, and sends preferred product bundles request to the SDA.
- Step 3: The SDA receives the request from the CA, determines the preferred product bundles as $\{P_1, P_2, P_3, P_4, P_1P_2, P_1P_3, P_1P_4, P_2P_3, P_2P_4, P_3P_4\}$ by the product bundle determination algorithm, and informs the preferred product bundles to the CA.
- Step 4: The CA receives the preferred product bundles from the SDA, creates eight instances of the BA {*BA*1, *BA*2, *BA*3, *BA*4, *BA*5,

Table 8
Function examples of purchasing company for the product bundle 1000.

Product bundle	Function example
Issue function	$V(I_1) = \exp\left(\left(1 - \frac{60-I_1}{60-50}\right)^{4.2} \ln 0.1\right)$ $V(I_3) = \exp\left(\left(1 - \frac{10-I_3}{10-1}\right)^{4.3} \ln 0.1\right)$ $V(\tilde{I}_2) = \frac{1}{6}(m_1 + 4m_2 + m_3)$ $V(\tilde{I}_4) = \frac{1}{6}(m_1 + 4m_2 + m_3)$
Utility function	$U(Bid) = 0.4 \times V(I_1) + 0.3 \times V(\tilde{I}_2) + 0.15 \times V(I_3) + 0.15 \times V(\tilde{I}_4)$
Concession function	$\alpha_1(t) = \alpha_2(t) = \alpha_3(t) = \alpha_4(t) = \exp((1-(t-1)/20)^{5.7} \ln 0.1)$
Generation function	$I_1(t) = \min_1 + \alpha_1(t) \times (\max_1 - \min_1)$ $I_3(t) = \min_3 + \alpha_3(t) \times (\max_3 - \min_3)$ $I_2 = \begin{cases} VP & 1-\alpha_2(t) \in [0, 0.125) \\ P & 1-\alpha_2(t) \in [0.125, 0.375) \\ M & 1-\alpha_2(t) \in [0.375, 0.625) \\ G & 1-\alpha_2(t) \in [0.625, 0.875) \\ VG & 1-\alpha_2 \in [0.875, 1] \end{cases}$ $I_4 = \begin{cases} VP & 1-\alpha_4(t) \in [0, 0.125) \\ P & 1-\alpha_4(t) \in [0.125, 0.375) \\ M & 1-\alpha_4(t) \in [0.375, 0.625) \\ G & 1-\alpha_4(t) \in [0.625, 0.875) \\ VG & 1-\alpha_4 \in [0.875, 1] \end{cases}$

Table 9
Function examples of supplier $S1$ for the product bundle 1000.

Product bundle	Function example
Issue function	$V(I_1) = \exp\left(\left(1 - \frac{I_1-550}{650-550}\right)^{3} \ln 0.1\right)$ $V(I_3) = \exp\left(\left(1 - \frac{10-I_3}{10-1}\right)^{4.3} \ln 0.1\right)$ $V(\tilde{I}_2) = \frac{1}{6}(m_1 + 4m_2 + m_3)$ $V(\tilde{I}_4) = \frac{1}{6}(m_1 + 4m_2 + m_3)$
Utility function	$U(Bid) = 0.4 \times V(I_1) + 0.3 \times V(\tilde{I}_2) + 0.15 \times V(I_3) + 0.15 \times V(\tilde{I}_4)$
Concession function	$\alpha_1(t) = \alpha_2(t) = \alpha_3(t) = \alpha_4(t) = \exp((1-(t-1)/10)^{5.3} \ln 0.1)$
Generation function	$I_1(t) = \max_1 - \alpha_1(t) \times (\max_1 - \min_1)$ $I_3(t) = \max_3 - \alpha_3(t) \times (\max_3 - \min_3)$ $I_2 = \begin{cases} VP & 0.1+\alpha_2(t) \in [0, 0.125) \\ P & 0.1+\alpha_2(t) \in [0.125, 0.375) \\ M & 0.1+\alpha_2(t) \in [0.375, 0.625) \\ G & 0.1+\alpha_2(t) \in [0.625, 0.875) \\ VG & 0.1+\alpha_2 \in [0.875, 1] \end{cases}$ $I_4 = \begin{cases} VP & 0.1+\alpha_4(t) \in [0, 0.125) \\ P & 0.1+\alpha_4(t) \in [0.125, 0.375) \\ M & 0.1+\alpha_4(t) \in [0.375, 0.625) \\ G & 0.1+\alpha_4(t) \in [0.625, 0.875) \\ VG & 0.1+\alpha_4(t) \in [0.875, 1] \end{cases}$

Table 10
Interactions of *BA1* and *S1*.

Round		Product bundle	Price	Quality	Delivery	Service	Quantity
1	$s \to b$	1000	650	VP	20	VP	1000,0,0,0
		0100	850	VP	30	VP	0,1000,0,0
		1100	1500	VP	25	VP	1000,1000,0,0
	$b \to s$	1000	510	VG	2	VG	1000,0,0,0
		0100	710	VG	3	VG	0,1000,0,0
		1100	1225	VG	3	VG	1000,1000,0,0
2	$s \to b$	1000	623	P	16	P	1000,0,0,0
		0100	823	P	25	P	0,1000,0,0
		1100	1433	P	20	P	1000,1000,0,0
	$b \to s$	1000	517	G	3	G	1000,0,0,0
		0100	717	G	4	G	0,1000,0,0
		1100	1245	G	4	G	1000,1000,0,0
3	$s \to b$	1000	601	M	13	M	1000,0,0,0
		0100	801	M	20	M	0,1000,0,0
		1100	1377	M	15	M	1000,1000,0,0
	$b \to s$	1000	528	G	4	G	1000,0,0,0
		0100	728	G	6	G	0,1000,0,0
		1100	1271	G	6	G	1000,1000,0,0
4	$s \to b$	1000	579	G	9	G	1000,0,0,0
		0100	779	G	16	G	0,1000,0,0
		1100	1323	G	11	G	1000,1000,0,0
	$b \to s$	1000	540	M	5	M	1000,0,0,0
		0100	740	M	9	M	0,1000,0,0
		1100	1301	M	9	M	1000,1000,0,0

*BA*6, *BA*7, *BA*8} for the eight suppliers {*S*1, *S*2, *S*3, *S*4, *S*5, *S*6, *S*7, *S*8}, and configures the negotiation strategies for the BA according to the parameters shown in Tables 3–6.

- Step 5: *BA*1 and *S*2, *BA*2 and *S*2, *BA*3 and *S*3, *BA*4 and *S*4, *BA*5 and *S*5, *BA*6 and *S*6, *BA*7 and *S*7, and *BA*8 and *S*8 start bilateral bargaining. These eight pairs of bilateral bargaining carry out concurrently in similar way. Table 7 shows the initial bids submitted by the eight suppliers. We use the bargaining between *BA*1 and *S*1 as example to explain the bargaining process.

- Step 5.1: *BA*1 calls for proposal from *S*1.
- Step 5.2: *S*1 proposes initial proposal with three bids {⟨(1000), 650, *VP*, 20, *VP*, (1000, 0, 0, 0)⟩, ⟨(0100), 850, *VP*, 30, *VP*, (0, 1000, 0, 0)⟩, ⟨(1100), 1500, *VP*, 25, *VP*, (1000, 1000, 0, 0)⟩} to *BA*1.

Table 11
Final bids submitted by suppliers (Experiment 1).

Supplier	Round	Bid id	Product bundle	Price	Quality	Delivery	Service	Quantity	Utility
S1	$4b \rightarrow s$	1	1000	540	M	5	M	1000,0,0,0	0.748
		2	0100	740	M	9	M	0,1000,0,0	0.748
		3	**1100**	**1301**	**M**	**9**	**M**	**1000,1000,0,0**	**0.748**
S2	$6b \rightarrow s$	4	1000	564	P	7	P	1000,0,0,0	0.499
		5	**0010**	**964**	**P**	**20**	**P**	**0,0,2000,0**	**0.499**
		6	1010	1560	P	20	P	1000,0,2000,0	0.499
S3	$9s \rightarrow b$	7	1000	624	P	27	P	1000,0,0,0	0.112
		8	0001	1244	P	22	P	0,0,0,2000	0.112
		9	1001	1861	P	27	P	1000,0,0,2000	0.112
S4	$6b \rightarrow s$	10	0100	764	P	13	P	0,1000,0,0	0.499
		11	0010	964	P	20	P	0,0,2000,0	0.499
		12	0110	1760	P	20	P	0,1000,2000,0	0.499
S5	$6b \rightarrow s$	13	0100	764	P	13	P	0,1000,0,0	0.499
		14	0001	1164	P	13	P	0,0,0,2000	0.499
		15	0101	1960	P	13	P	0,1000,0,2000	0.499
S6	$5b \rightarrow s$	16	0010	1020	M	11	M	0,0,2000,0	0.371
		17	0001	1210	M	16	M	0,0,0,2000	0.289
		18	0011	2210	M	11	M	0,0,2000,2000	0.504
S7	$7b \rightarrow s$	19	0100	774	P	15	P	0,1000,0,0	0.400
		20	0001	1174	P	15	P	0,0,0,2000	0.400
S8	$4b \rightarrow s$	21	0010	952	M	16	M	0,0,2000,0	0.697
		22	**0001**	**1152**	**M**	**11**	**M**	**0,0,0,2000**	**0.697**

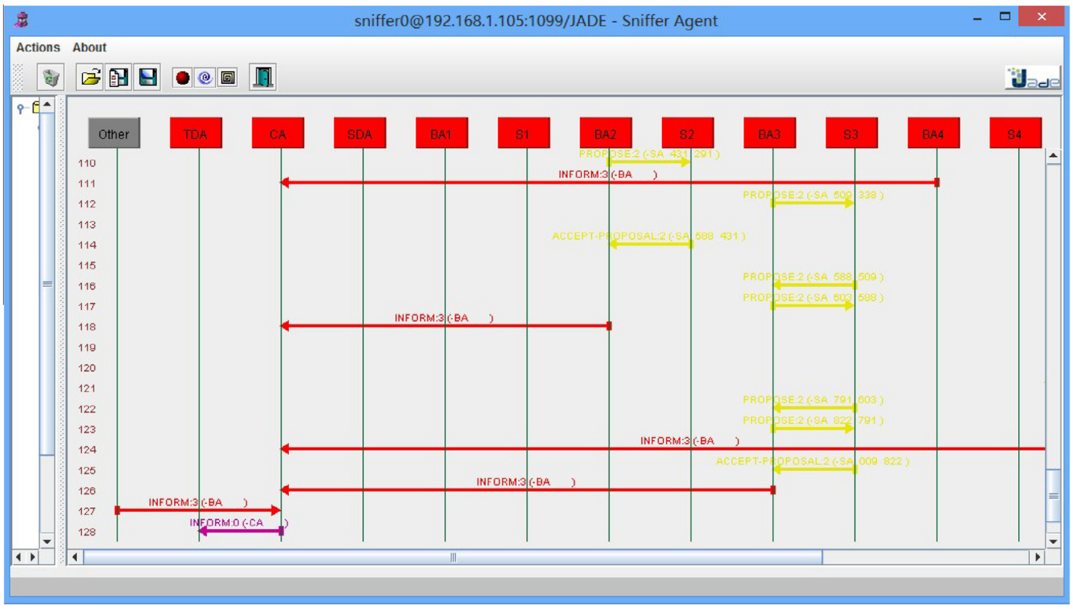

Fig. 6. Tracing diagram of agents involving in the proposed negotiation model.

- Step 5.3: *BA*1 evaluates the proposal proposed by *S*1 by Eqs. (1)–(4) with corresponding parameters bid-by-bid, the concession rate of each issue is determined by Eq. (5) with corresponding parameters, the contents of counter-bids, and the responding decision are determined by Eqs. (6) and (7) with corresponding parameters. For instance, Table 8 shows the examples of issue utility function, bid utility function, concession function and generation function of *BA*1 for the product bundle 1000. If *BA*1 accepts all the bids of a proposal, *BA*1 accepts the proposal; otherwise, *BA*1 proposes a counter-proposal or quits the bargaining. For instance, in the 1st negotiation round, *BA*1 rejects the receiving proposal and proposes the counter-proposal {⟨(1000), 510, *VG*, 2, *VG*, (1000, 0, 0, 0)⟩, ⟨(0100), 710, *VG*, 3, *VG*, (0, 1000, 0, 0)⟩, ⟨(1100), 1225, *VG*, 3, *VG*, (1000, 1000, 0, 0)⟩}.
- Step 5.4: *S*1 receives *BA*1's counter-proposal and evaluates the counter-proposal bid-by-bid. If *S*1 accepts all the bids in the counter-proposal, *S*1 accepts the counter-proposal, otherwise *S*1 proposes a proposal in a similar way as *BA*1. Table 9 shows the examples of issue utility function, bid utility function, concession function and generation function of *S*1 for the product bundle 1000.

Table 12
Experiment results on different deadlines ($\gamma = 5.7$).

t_{max}	Supplier	Bid	Bid utility	Solution utility
10	*S*1	⟨(1100), 1331, M, 11, M, (1000,1000,0,0)⟩	0.697	0.575
	*S*6	⟨(0011), 2223, M, 12, M, (0,0,2000,2000)⟩	0.453	
20	*S*1	⟨(1100), 1301, M, 9, M, (1000,1000,0,0)⟩	0.748	0.648
	*S*2	⟨(0010), 964, P, 20, P, (0,0,2000,0)⟩	0.499	
	*S*8	⟨(0001), 1152, M, 11, M, (0,0,0,2000)⟩	0.697	
30	*S*1	⟨(1100), 1271, G, 6, G, (1000,1000,0,0)⟩	0.881	0.808
	*S*6	⟨(0011), 2111, M, 14, M, (0,0,2000,2000)⟩	0.735	

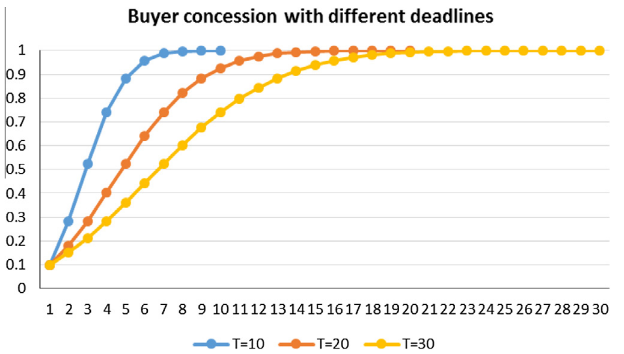

Fig. 7. Purchasing company's concession process with different negotiation deadlines.

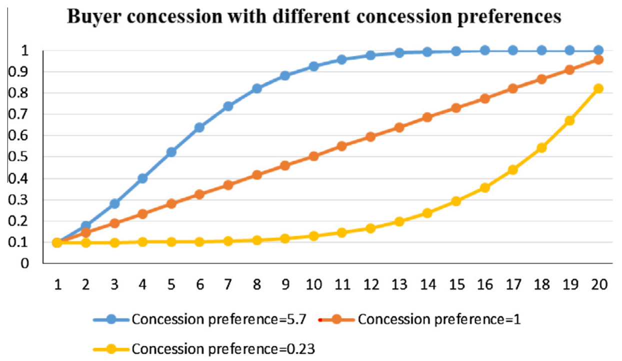

Fig. 8. Purchasing company's concession process with different concession preferences.

- Step 5.5: *BA*1 and *S*1 repeat step 5.3 and step 5.4 until agreement or the negotiation deadline ($t_{max} = 20$ rounds) is reached. In this example, *BA*1 and *S*1 reach agreement as {⟨(1000), 540, *M*, 5, *M*, (1000, 0, 0, 0)⟩, ⟨(0100), 740, *M*, 9, *M*, (0, 1000, 0, 0)⟩, ⟨(1100), 1301, *M*, 9, *M*, (1000, 1000, 0, 0)⟩}. Table 10 shows the interaction process of *BA*1 and *S*1.
- Step 6: After all the eight pair of the BA and SA completing bilateral bargaining, the *BA*1, *BA*2, *BA*3, *BA*4, *BA*5, *BA*6, *BA*7 and *BA*8 informs the negotiation results as shown in Table 11 to the CA. Fig. 5 shows the concession process of the purchasing company and suppliers.
- Step 7: The CA selects the solution $\{Bid_3, Bid_5, Bid_{22}\}$ (bold font in Table 11) with the maximal solution utility $(0.748 + 0.499 + 0.697)/3 = 0.648$ as the optimal solution by the B&B-based winner determination algorithm. Consequently, the cooperative suppliers which are the submitters of the bids in the optimal solution are *S*1, *S*2 and *S*8.

As shown in Fig. 6, the interactions of agents involving in the negotiation model for multi-product supplier selection are governed by the proposed negotiation protocol. The optimal solution $\{Bid_3, Bid_5, Bid_{22}\}$ is selected and the cooperative suppliers *S*1, *S*2 and *S*8 are determined. It demonstrates that the proposed negotiation model is able to conduct supplier selection for multiple products with synergy effect.

5.2. Experiment 2: effectiveness of the negotiation model for multi-product supplier selection

Tests are conducted to evaluate the performances of the proposed negotiation model under two conditions.

Firstly, the purchasing company adopts different negotiation deadlines, namely, $t_{max} = 10$ rounds, $t_{max} = 20$ rounds, and $t_{max} = 30$ rounds, with the concession preference fixed at $\gamma = 5.7$. Fig. 7 shows the concession process of the purchasing company with different negotiation deadlines, and the negotiation results are listed in Table 12. As shown in Table 12, different deadlines result in different optimal solutions (0.575, 0.648, and 0.808 respectively), with the corresponding cooperative suppliers ({*S*1,*S*6}, {*S*1,*S*2,*S*8}, and {*S*1,*S*6} respectively). The results indicate that the negotiation

Table 13
Experiment results on different concession preferences ($t_{max} = 20$).

Concession preference	Supplier	Bid	Bid utility	Solution utility
$\gamma = 5.7$	*S*1	⟨(1100), 1301, M, 9, M, (1000,1000,0,0)⟩	0.748	0.648
	*S*2	⟨(0010), 964, P, 20, P, (0,0,2000,0)⟩	0.499	
	*S*8	⟨(0001), 1152, M, 11, M, (0,0,0,2000)⟩	0.697	
$\gamma = 1$	*S*1	⟨(1100), 1259, G, 5, G, (1000,1000,0,0)⟩	0.885	0.825
	*S*6	⟨(0011),2081, M, 10, M, (0,0,2000,2000)⟩	0.764	
$\gamma = 0.23$	*S*1	⟨(1000), 510, G, 2, G, (1000,0,0,0)⟩	0.888	0.888
	*S*4	⟨(0110), 1629,G, 4, G, (0,1000,2000,0)⟩	0.888	
	*S*5	⟨(0001), 1114, G, 4, G, (0,0,2000,2000)⟩	0.887	

Table 14
Initial bids submitted by suppliers (Experiment 3).

Bid Id	Product bundle	Price	Quality	Delivery	Service	Quantity	Supplier
1	1000	650	VP	20	VP	1000,0,0,0	*S*1
2	0100	850	VP	30	VP	0,1000,0,0	*S*1
3	1000	660	VP	20	VP	1000,0,0,0	*S*2
4	0010	1040	VP	40	VP	0,0,2000,0	*S*2
5	1000	640	VP	25	VP	1000,0,0,0	*S*3
6	0001	1260	VP	30	VP	0,0,0,2000	*S*3
7	0100	850	VP	40	VP	0,1000,0,0	*S*4
8	0010	1050	VP	30	VP	0,0,2000,0	*S*4
9	0100	860	VP	20	VP	0,1000,0,0	*S*5
10	0001	1240	VP	25	VP	0,0,0,2000	*S*5
11	0010	1060	VP	15	VP	0,0,2000,0	*S*6
12	0001	1250	VP	20	VP	0,0,0,2000	*S*6
13	0100	840	VP	15	VP	0,1000,0,0	*S*7
14	0001	1240	VP	18	VP	0,0,0,2000	*S*7
15	1000	1040	VP	20	VP	1000,0,0,0	*S*8
16	0100	1250	VP	15	VP	0,1000,0,0	*S*8

Table 15
Final bids submitted by suppliers (Experiment 3).

Supplier	Round	Bid id	Product bundle	Price	Quality	Delivery	Service	Quantity	Utility
***S*1**	$4b \rightarrow s$	**1**	**1000**	**540**	**M**	**5**	**M**	**1000,0,0,0**	**0.748**
		2	0100	740	M	9	M	0,1000,0,0	0.748
*S*2	$6b \rightarrow s$	3	1000	564	P	7	P	1000,0,0,0	0.499
		4	0010	964	P	20	P	0,0,2000,0	0.499
*S*3	$9s \rightarrow b$	5	1000	624	P	27	P	1000,0,0,0	0.112
		6	0001	1244	P	22	P	0,0,0,2000	0.112
***S*4**	$6b \rightarrow s$	7	0100	764	P	13	P	0,1000,0,0	0.499
		8	**0010**	**964**	**P**	**20**	**P**	**0,0,2000,0**	**0.499**
***S*5**	$6b \rightarrow s$	**9**	**0100**	**764**	**P**	**13**	**P**	**0,1000,0,0**	**0.499**
		10	0001	1164	P	13	P	0,0,0,2000	0.499
*S*6	$5b \rightarrow s$	11	0010	1020	M	11	M	0,0,2000,0	0.371
		12	0001	1210	M	16	M	0,0,0,2000	0.289
*S*7	$7b \rightarrow s$	13	0100	774	P	15	P	0,1000,0,0	0.400
		14	0001	1174	P	15	P	0,0,0,2000	0.400
***S*8**	$4b \rightarrow s$	15	0010	952	M	16	M	0,0,2000,0	0.697
		16	**0001**	**1152**	**M**	**11**	**M**	**0,0,0,2000**	**0.697**

model is sensitive to negotiation time, and the longer the negotiation deadline the better the negotiation results for the purchasing company.

Secondly, the purchasing company adopts different concession preferences. In the tests, the deadline is set at $t_{\max} = 20$, we assign $\gamma = 5.7$, $\gamma = 1$, and $\gamma = 0.23$ respectively to reflect these preferences. Fig. 8 shows the concession process of the negotiation model for the purchasing company with different concession preferences, and the negotiation results are shown in Table 13. Here, different concession preferences ($\gamma = 5.7$, 1, and 0.23) generate different optimal solutions (0.648, 0.825, and 0.888 respectively), correspond to the cooperative suppliers ({*S*1,*S*2,*S*8}, {*S*1,*S*6}, and {*S*1,*S*4,*S*5} respectively). Comparison of the negotiation results indicates that the negotiation model is sensitive to the conceding strategy.

The results of Experiment 2 shows that the purchasing company can represent its real needs by configuring the parameters involving in the negotiation process, for instance, negotiation deadline $t_{\max}$, concession preference γ, and so on. The decision maker also can adjust the values of issue value space $[\min_k, \max_k]$, weight ω_k, and risk preference β to represent its preferences on the multiple products with synergy effect.

5.3. Experiment 3: efficiency of the negotiation model for multi-product supplier selection

In order to evaluate the efficiency of the proposed negotiation model, the negotiation model without considering the synergy effect between products is conducted under the same parameter settings as Experiment 1. Table 14 shows the initial bids submitted by suppliers {*S*1, *S*2, *S*3, *S*4, *S*5, *S*6, *S*7, *S*8}. After negotiating with these suppliers, the final bids submitted by suppliers are obtained as shown in Table 15. Through the B&B-based winner determination algorithm, solution $\{Bid_1, Bid_8, Bid_9 Bid_{16}\}$ (using bold font in Table 15) with the maximal solution utility $(0.748 + 0.499 + 0.499 + 0.697)/4 = 0.611$ is selected. In such case, the cooperative suppliers are *S*1, *S*4, *S*5 and *S*8.

5.4. Remarks on the simulation results of the negotiation model for multi-product supplier selection

As illustrated in the simulation results of the different test cases, the agent-based negotiation model is able to select cooperative suppliers for multiple products with synergy effect. Both the purchasing company and suppliers' preferences on products can be represented by the proposed negotiation model. In practice, the purchasing company can represent its preferences on the synergy effect between the products by assigning the parameters of the proposed negotiation model.

According to the selection results of Experiment 1 and Experiment 3, when the synergy effect between products are considered (Experiment 1), the cooperative suppliers are *S*1, *S*2 and *S*8 with solution utility 0.648 (Table 11); while the synergy effect between products are not considered (Experiment 3), the cooperative supplier are *S*1, *S*4, *S*5, and *S*8 with solution utility 0.611 (Table 15).

These selection results indicate that, when the synergy effect between products is not considered, more cooperative suppliers are needed for the required products, and smaller utility is obtained. In other words, when synergy effect between products is considered, the purchasing company can obtain more satisfying solution and fewer cooperative suppliers. In such case, the selected cooperative suppliers can make full use of their resources. In addition, when the synergy effect between products is considered, more types of bids are allowed which represents the preferences of the purchasing company and suppliers more sufficiently. For instance, in Experiment 1, 10 types of bids are negotiated; while in Experiment 3, only 4 types of bids are allowed. Incorporating the synergy effect between products in the multi-product supplier selection environment can enhance the efficiencies of the purchasing company and suppliers.

In conclusion, the agent-based negotiation model for supplier selection of multiple products with synergy effect is practical and effective in practice. Both the purchasing company and suppliers can benefit from the proposed negotiation model.

6. Conclusion and future work

In this paper, an agent-based negotiation model for supplier selection of multiple products with synergy effect is implemented. Firstly, the MAS supporting the proposed negotiation model for multi-product supplier selection is developed. Secondly, the negotiation proposal, negotiation protocol, negotiation strategies, and decision making methods involving in the negotiation model are elaborated for the multi-product supplier selection environment. Thirdly, the purchasing company and suppliers can reach agreements on the details of products simultaneously and exploit the synergy effect between products. Finally, the function and effectiveness of the agent-based negotiation model for multi-product supplier selection are demonstrated. This is an original negotiation model for multi-product supplier selection incorporating the synergy effect between products. The preferences of decision makers on products with synergy effect can be represented more sufficiently by the proposed negotiation model.

Since multiple products can be procured simultaneously and synergy effects between products are considered, the proposed agent-based negotiation model is more realistic than previous studies. The procurement departments of enterprises can use this model to select optimal suppliers for multiple products/services simultaneously. In addition, with the help of this model, enterprises can make full use of the positive synergies between products in the multi-product supplier selection environment to reduce cost and enhance efficiency.

While there are still some areas reserved to further research. Firstly, the number of products in current experiments is small. In future, we will extend the model to realize the procurement of a large number of products. Secondly, in the proposed negotiation model, decision makers represent their preferences on products by assigning parameters in advance. In future, more research is conducted to improve the intelligence and automation of the negotiation model, and then agents could dynamically elicit the negotiation strategies to represent decision makers' preferences on products. Finally, the proposed negotiation model will be applied to real applications to further verify its effectiveness.

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