Feasible Negotiation Procedures for Multiple Interdependent Negotiations

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ABSTRACT

Within an agent society, agents utilise their knowledge differently to achieve their individual or joint goals. Agent negotiation provides an effective solution to help agents reach agreements on their future behaviour in the society to guarantee their goals can be achieved successfully. Agents may need to conduct Multiple Interdependent Negotiations (MIN) with different opponents and for different purposes, in order to achieve a goal. By considering the complexity of negotiation environments, interdependencies, opponents and issues in the agent society, conducting MIN efficiently is a challenging research issue. To the best of the authors' knowledge, most of the state-of-art work primarily focuses on single negotiation scenarios and tries to propose sophisticated negotiation protocols and strategies to help individual agents to succeed in single negotiation. However, very little work has been done while considering interdependencies and trade-offs among multiple negotiations, so as to help both individual agents as well as the agent society, to increase their welfare. This paper promotes the research on agent negotiation from the single negotiation level to the multiple negotiations level. To effectively conduct MIN in an agent society, this paper proposes three feasible *negotiation procedures*, which attempt to conduct MIN in a successive way, in a concurrent way, and in a clustered way while considering them in different negotiation situations, respectively. A simulated agent society is built to test the proposed negotiation procedures with random experimental settings. According to the experimental results, the *successive negotiation procedure* produces the highest time efficiency, the *concurrent negotiation procedure* promises the highest profits and success rates, whilst the *clustered negotiation procedure* provides a well-balanced solution between negotiation efficiency and effectiveness.

KEYWORDS

Multiple interdependent negotiations; negotiation procedures; social welfare

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1 INTRODUCTION

In an agent society, agents usually have different knowledge and goals, utilising these differently to achieve their individual or joint goals. Agent negotiation provides an effective solution between agents and helps them to achieve a mutually beneficial negotiation agreement, which will guide agents' behaviour in the society and lead them to successfully achieve their goals. To date, most of the existing work on agent negotiations [4, 5, 9, 10] deals almost exclusively with single negotiations, and attempts to propose sophisticated solutions to improve agents' profits in single negotiations. To the best of the authors' knowledge, very little work has been done while considering interdependencies and trade-offs among multiple negotiations, so as to help both individual agents as well as the agent society, to increase their welfare.

In an agent society, agents may conduct multiple interactions with each other and would need to conduct Multiple Interdependent Negotiations (MIN) with different opponents and for different purposes to achieve their goals. By considering the complexity of negotiation environments, interdependencies, opponents and issues in the agent society, to effectively conduct MIN is a challenging research issue. For instance, through using the Internet, a travel agent can interact with other agents for a trip package with a budget and time requirement, which may include a flight, accommodation and some tourist activities. Typically, the agent will conduct multiple negotiations for flights, accommodations and activities, respectively, and these negotiations are interdependent when considering the factors of budget, sequence and time. During the negotiations, the agent's goal is to achieve a series of negotiation agreements with the minimal price and a suitable schedule to satisfy the budget and the time requirement. To achieve such a goal, an appropriate negotiation procedure must be used to conduct these negotiations, and this is still a challenging research issue in agent negotiation.

Usually, the interdependency between MIN is determined by the interdependencies of negotiation issues included within the MIN. Figure 1 shows an example of issue interdependencies which could exist within MIN. The three big circles indicate three negotiations, i.e., N_0, N_1 and N_2; and the dots, squares and triangles in the big circles indicate negotiation

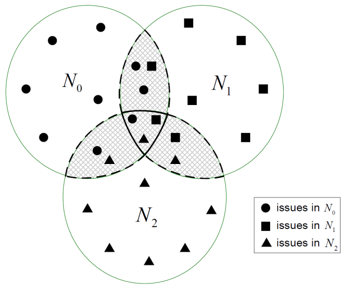

Figure 1: An example of issue interdependencies in MIN

issues included by the three negotiations, respectively. The overlapped shaded areas between MIN indicate the interdependencies of their negotiation issues. In current literature, a large amount of work exclusively studies the issue interdependency within a particular multi-issue negotiation [2, 5, 9, 11], which is represented by the non-shaded areas in Figure 1. Three general *issue procedures* [6, 7] are well known by researchers, which are the simultaneous procedure, the sequential procedure and the package deal procedure. By using these *issue procedures*, a single negotiation with multiple issues can be effectively processed. However, very little work considers issue interdependencies across MIN in the research of agent negotiation due to the complexities of MIN. Hemaissia et al. [8] proposed a multilateral negotiation protocol with consideration of dependencies between issues. However, this approach only deals with issue dependencies in a single negotiation. Mansour et al. [15] proposed an approach to handle multiple negotiations, however, issue interdependencies between multiple negotiations were not considered.

This paper aims to address this gap in the existing agent negotiation research. Through studying the issue interdependency across MIN, feasible *negotiation procedures* for effectively conducting MIN are proposed to help agents achieve multiple negotiation agreements so as to direct their methods to achieve success in an agent society. This paper promotes the current research on agent negotiation from the single negotiation level to the multiple negotiations level. To address the challenge of the *negotiation procedure* in MIN, three research problems have to be considered in this paper: 1) how to model the MIN, 2) how to generate negotiation offers by considering issue interdependencies across MIN, and 3) how to conduct negotiations in MIN. For the first research problem, this paper proposes a general MIN model by using a negotiation network; for the second research problem, this paper proposes an approximating Pareto-optimal offer generating strategy; and for the third research problem, this paper proposes three feasible *negotiation procedures* for conducting MIN, i.e., the *successive negotiation procedure*, the *concurrent negotiation procedure* and the *clustered negotiation procedure*. The analysis of the three proposed negotiation procedures is also given based on the experimental results.

The organisation of this paper is as follows. Section 2 presents a general MIN model. Section 3 proposes an offer generation strategy while considering issue interdependencies across MIN. Section 4 proposes three negotiation procedures for conducting MIN. Section 5 introduces an experimental analysis of the proposed solutions. Sections 6 and 7 present related work and the conclusion of this paper, respectively.

2 A GENERAL MODEL FOR MIN

This section proposes a general MIN model. The MIN conducted by an agent can form a negotiation network. In this negotiation network, the agent negotiates with different opponents in different negotiations, and each negotiation contains different numbers of negotiation issues. Such a negotiation network for an agent can be formalised as follows.

Let $\Theta = \{\mathbb{N}, \mathbb{A}, \mathbb{S}, \mathbb{O}, \mathbb{I}\}$ be a negotiation network in which Agent a conducts an MIN. In details, let

- $\mathbb{N} = \{N_0, \cdots N_i, \cdots\ N_m\} (i \geq 0)$ denote a set of negotiations involved in the MIN, where N_i indicates a bilateral single-issue/multi-issue negotiation;
- $\mathbb{A} = \{a_{N_0}, \cdots a_{N_i}, \cdots a_{N_m}\}\ (i \geq 0)$ denote a set of Agent a's negotiation opponent in every single negotiation, where a_{N_i} is Agent a's opponent in Negotiation N_i;
- $\mathbb{S} = \{\mathbb{S}_{N_0}, \cdots \mathbb{S}_{N_i},\ \cdots \mathbb{S}_{N_m}\} (i \geq 0)$ denote a set of issue sets for every single negotiation, where $\mathbb{S}_{N_i} = \{s_0, \cdots s_j, \cdots s_n\} (j \geq 0)$ denotes all issues included within Negotiation N_i;
- $\mathbb{O} = \{\mathbb{F}_{N_0}, \cdots \mathbb{F}_{N_i}, \cdots \mathbb{F}_{N_m}\} (i \geq 0)$ denote a set of offer sets for all negotiations, where $\mathbb{F}_{N_i} = \{\mathbb{O}_a, \mathbb{O}_{a_{N_i}}\}$ indicates a set of offer sets for Negotiation N_i. $\mathbb{O}_a = \{o_a^{t_0}, \cdots o_a^{t_k}, \cdots o_a^{t_l}\}$ is a set of offers proposed by Agent a in Negotiation N_i, and $\mathbb{O}_{a_{N_i}} = \{o_{a_{N_i}}^{t_0}, \cdots o_{a_{N_i}}^{t_r}, \cdots o_{a_{N_i}}^{t_h}\}$ is a set of counter-offers proposed by Opponent a_{N_i} in Negotiation N_i, e.g., $o_{a_{N_i}}^{t_r}$ indicates a counter-offer given by Opponent a_{N_i} in Negotiation N_i at period t_r;
- $\mathbb{I} = \{i_0, \cdots i_p, \cdots i_q\}$ indicate a set of issue interdependencies, where $i_p = \{s_l \backsim \cdots \backsim s_m \backsim \cdots \backsim s_n | (s_l, \cdots s_m, \cdots s_n) \in \mathbb{S}_{N_i} \times \cdots \times \mathbb{S}_{N_j} \times \cdots \times \mathbb{S}_{N_k}\}$ indicates a set of issues satisfying an *issue interdependency* defined by Definition 1.

In the proposed MIN model, each single Negotiation N_i is defined as a bilateral negotiation, i.e., the negotiation involves exactly two agents. A conventional multilateral negotiation, i.e., the negotiation involves multiple agents, is represented by multiple bilateral negotiations with the exactly same negotiation settings. Therefore, the proposed MIN model is general and can cover all possible negotiation scenarios.

The formal definition of the issue interdependency across MIN is introduced as follows.

Definition 1. ***(Issue Interdependency)*** *Let* $i_p = \{s_l \backsim \cdots \backsim s_m \backsim \cdots \backsim s_n | (s_l, \cdots s_m, \cdots s_n) \in \mathbb{S}_{N_i} \times \cdots \times \mathbb{S}_{N_j} \times \cdots \times \mathbb{S}_{N_k}\}$ *denote an* ***issue interdependency*** *between multiple issues in MIN, and it reflects an interactive restriction between* *issues across multiple negotiations. Specifically, $s_l \backsim s_m$ indicates that the sub-offer on Issue s_l in Negotiation N_i and the sub-offer on Issue s_m in Negotiation N_j are influenced with each other, and $s_l \backsim s_m \Leftrightarrow s_m \backsim s_l$.*

Let $o_a^t \in \mathbb{O}_a (i.e., \mathbb{O}_a \in \ \mathbb{F}_N, N \in \mathbb{N})$ denote the offer given by Agent a at negotiation period t in Negotiation N, and $o_a^t(s)$ $(s \in \mathbb{S}_N)$ indicates the sub-offer on Issue s. Assuming an issue interdependency is $s_l \backsim \cdots \backsim s_m \backsim \cdots \backsim s_n$, Equation (1) represents the mathematical relationship between issues in an issue interdependency.

$$\sum_{m=l}^{n} \left(\mu_m \times o_{N_j}^{t_k}(s_m)\right) \leq Q, \tag{1}$$

where μ_m is the coefficient for the sub-offer on Issue s_m in Negotiation N_j and Q is a constant, t_k indicates a negotiation period.

3 OFFER GENERATION STRATEGY IN MIN

Agent a's strategy of generating offers in single multi-issue negotiation is not the focus of this paper. Therefore, we adopt the "shortest distance strategy" [12, 13] and do an extension to handle issue interdependencies across MIN. The reason why this strategy is employed is that the "shortest distance strategy" has been proved to be one of the strategies which could generate an approximating Pareto-optimal solution in the multi-issue negotiation. The core idea of the "shortest distance strategy" is to always select the point which has the shortest distance with the point on its opponent's indifference curves (surfaces) (i.e., points on an agent's indifference curves (surfaces) denote the same utility for the agent).

To better describe agent's strategy affected by issue interdependencies, "Edgeworth-Bowley Box" [21] is employed, which is frequently utilised in "equilibrium theory" and it aids in bargaining problems of game theory. To simplify the discussion, we take a simple negotiation scenario as an example, where Agent a conducts an MIN with its opponents. One of the negotiations in the MIN is N_0, Agent a's opponent in Negotiation N_0 is a_{N_0}, the negotiation issues are s_0 and s_1. Issue s_1 may have an interdependency with issues in other negotiations, e.g., $i_0 = \{s_1 \backsim \cdots \backsim s_m \backsim \cdots \backsim s_n | (s_1, \cdots s_m, \cdots s_n) \in \mathbb{S}_{N_0} \times \cdots \times \mathbb{S}_{N_j} \times \cdots \times \mathbb{S}_{N_k}\}$. Figure 2 shows Agent a's strategy of generating offers while considering the issue interdependency i_0 across MIN.

At period $t_0 - 1$ (see Figure 2), Agent a's opponent a_{N_0} proposes a counter-offer $o_{a_{N_0}}^{t_0-1}$ to Agent a. At period t_0, if Issue s_1 is not involved in the issue interdependency i_0, Agent a selects an offer $o_a^{t_0}$, represented by a black square, which has the shortest distance with the point $o_{a_{N_0}}^{t_0-1}$. However, if Issue s_1 is involved in the issue interdependency i_0, Agent a selects an offer $\tilde{o}_a^{t_0}$, represented by a black dot, which simultaneously satisfies conditions of having the shortest distance with the point $o_{a_{N_0}}^{t_0-1}$ and falling in the shaded area $P_a^{t_0}$, where the shaded area $P_a^{t_0}$ is calculated by the mathematical restriction of the issue interdependency i_0 between Issue s_1

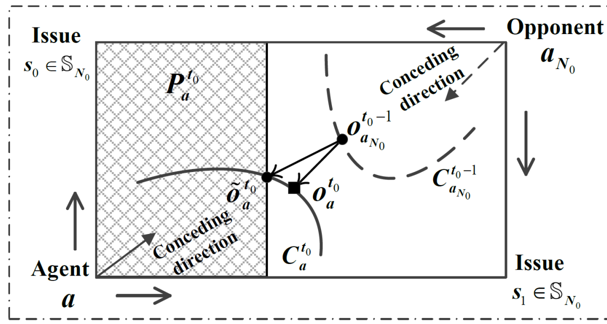

Figure 2: Edgeworth-Bowley box for agent's strategy affected by issue interdependencies across MIN

and other issues involved in the issue interdependency. The values of the sub-offers on these other issues are the last values offered in their corresponding negotiations. Based on these values and the mathematical restriction of the issue interdependency i_0, the value range of the sub-offer on Issue s_1 can be calculated, then the shaded area $P_a^{t_0}$ is determined. By employing the strategy, the negotiation is conducted until an offer is accepted or a deadline is reached.

4 NEGOTIATION PROCEDURES FOR MIN

The negotiation procedure for MIN indicates how agents conduct an MIN, which is crucial to the success of conducting the MIN. Let $\mathbb{N} = \{N_0, \cdots N_i, \cdots N_m\}$ be an MIN conducted by Agent a, where N_i denotes a bilateral single-issue/multi-issue negotiation. It is assumed that Agent a has its private preference on the importance of each negotiation in the MIN. The preference can be represented by a set $\mathbb{V} = \{\nu_0, \cdots \nu_i, \cdots \nu_m\}$, where ν_i indicates the importance of Negotiation N_i for Agent a. This section proposes the following three negotiation procedures to conduct MIN in different situations.

(1) Successive Negotiation Procedure

In the successive negotiation procedure, the agent processes multiple negotiations one after another. The sequence of processing these negotiations is dependent on the importance of negotiations. That is to say, the agent always firstly processes the most important negotiation. After the former negotiation is completed, the agent processes the next one. Once a negotiation is completed, all issues in the completed negotiation have been settled. The agent's decision-makings in the latter negotiations are affected by the interdependencies from the settled issues in completed negotiations.

Algorithm 1 shows the successive negotiation procedure for processing an MIN conducted by Agent a. In Algorithm 1, the input is a negotiation network Θ_a involving an MIN, and the output is outcomes of all negotiations in the MIN. Firstly, Agent a sorts all m negotiations based on their importance, and gets a negotiation sequence, e.g., $N_0 \rightarrow \cdots \rightarrow N_i \rightarrow \cdots \rightarrow N_m$ (Line 3). Then Agent a conducts all negotiations based on the negotiation sequence.

Algorithm 1: Successive Negotiation Procedure

1 **Input:** a negotiation network Θ_a, involving an MIN.
2 **Output:** the outcomes of all negotiation in the MIN.
3 **Pre-calculations**: sort all m negotiations in the MIN based on their importance and get the negotiation sequence, e.g., $N_0 \rightarrow \cdots \rightarrow N_i \rightarrow \cdots \rightarrow N_{m-1}$, where $\nu_0 \geq \cdots \geq \nu_i \geq \cdots \geq \nu_{m-1}$.
4 **for** $i \leftarrow 0$ *to* $m-1$ **do**
5   **if** *issues in Negotiation* N_i *have issue interdependencies with issues in other negotiations* **then**
6   retrieve all latest values of sub-offers on issues related in issue interdependencies and store the values in a list *lis*
7   conduct Negotiation N_i using the proposed strategy in Section 3 while considering the values in the list *lis*
8   **if** *Negotiation* N_i *is completed* **then**
9   record the result of Negotiation N_0, i.e., success or failure, and calculate the utility achieved in Negotiation N_i, i.e., $U(N_i)$
10   $i \leftarrow i+1$
11 **return** the outcomes of all negotiations in the MIN

During conducting a negotiation (e.g., N_i), the agent checks interdependencies of issues in Negotiation N_i, then retrieves all last values of sub-offers on the issues, which have issue interdependencies with issues in Negotiation N_i (Lines 5-6). Agent a adopts the proposed strategy in Section 3 to negotiate with its opponent (Line 7). For each completed negotiation, Agent a records the result of the negotiation and calculates the utility achieved in the negotiation (Lines 8-9). Agent a follows the same procedure to successively conduct all m negotiations until all of them are completed.

(2) Concurrent Negotiation Procedure

In the concurrent negotiation procedure, the agent concurrently processes all negotiations. The agent's decision-makings in each negotiation are affected by issue interdependencies across MIN during the negotiation process.

As very limited work exits on solving the problem of concurrently handling MIN, this paper proposes the following transition system-based approach to solve this problem. To handle the concurrency in MIN, a transition system is employed in the concurrent negotiation procedure.

A general transition system TS is a tuple $TS =< S, I, Act, G >$ [3], where S indicates a set of states, I indicates a set of initial states and $I \subseteq S$, $Act = \{a_0, \cdots a_i, \cdots a_c\}$ is a set of actions, where $a_i \in S \times S$ and G is a set of final states and $G \subseteq S$.

Based on the definition of the general transition system, we define a transition system-based representation of multiple negotiations as follows.

A set of negotiations $\mathbb{N} = \{N_0, \cdots N_i, \cdots N_m\}$ in a negotiation network Θ_a can be represented by a concurrent system $TS_{\mathbb{N}} = TS_{N_0}|| \cdots ||TS_{N_i}|| \cdots ||TS_{N_m}$, where TS_{N_i} indicates a transition system-based representation of Negotiation N_i, i.e., $TS_{N_i} =< S, I, Act, G, cs >$, where $S = \{initial, ongoing, failure, success\}$, $I = \{initial\}$, $Act = \{(initial, ongoing), (ongoing, ongoing), (ongoing, failure), (ongoing, success)\}$, $G = \{failure, success\}$, and $cs \in S$ indicates the current state of Negotiation N_i.

Algorithm 2 shows the concurrent negotiation procedure for conducting MIN. The concurrency of MIN is handled by the proposed transition system-based approach.

Algorithm 2: Concurrent Negotiation Procedure

1 **Input:** a negotiation network Θ_a, involving an MIN.
2 **Output:** the outcomes of all negotiations in the MIN.
3 **Pre-calculations**: calculate the transition system $TS_{\mathbb{N}}$.
4 concurrently start conducting all m negotiations in the MIN
5 **while** *not all negotiations are completed* **do**
6   **if** *Agent a receives a counter-offer from its opponent in Negotiation* N_i **then**
7   retrieve all last values of sub-offers on issues in other negotiations which have interdependencies with issues in Negotiation N_i, and store the values in a list *lis*
8   adopt the proposed strategy in Section 3 while considering the values in the list *lis*
9   **if** *Negotiation* N_i *is completed* **then**
10   record the result of Negotiation N_0, i.e., success or failure, and calculate the utility achieved in Negotiation N_i, i.e., $U(N_i)$
11 **return** the outcomes of all negotiations in the MIN

In Algorithm 2, the input is a negotiation network Θ_a involving an MIN, and the output is the outcomes of all negotiations in the MIN. First, the transition system $TS_{\mathbb{N}}$ is precalculated based on the negotiation network Θ_a (Line 3). The Agent a concurrently starts conducting all negotiations in the MIN (Line 4). During the negotiations, if Agent a receives a counter-offer from its opponent in Negotiation N_i, Agent a checks the issue interdependencies and retrieves all last values of sub-offers on the issues, having interdependencies with issues in Negotiation N_i (Lines 6-7). Agent a adopts the proposed strategy in Section 3 to negotiate with its opponent (Line 8). For each completed negotiation, Agent a records the result of the negotiation and calculates the utility achieved in the negotiation (Lines 9-10). All m negotiations are concurrently conducted until all of them are completed.

(3) Clustered Negotiation Procedure

In the clustered negotiation procedure, all m negotiations are firstly partitioned into $\mu > 1$ disjoint subsets, where each subset is called a *negotiation cluster* in this paper. The negotiations in each negotiation cluster are processed by using the *concurrent negotiation procedure*. Then, Agent a processes all negotiation clusters by using the *successive negotiation procedure*. Once a negotiation cluster is completed (i.e., all negotiations in the negotiation cluster are completed), all issues in the completed negotiation cluster have been settled, and the agent's decision-makings in latter negotiation clusters are affected by the issue interdependencies from the completed negotiation clusters. In general, the *clustered negotiation procedure* can cover both the *successive negotiation procedure* and the *concurrent negotiation procedure*. For example, when $\mu = m$, we have m negotiation clusters which turns the *clustered negotiation procedure* into the *successive negotiation procedure*; when $\mu = 1$, we have only one negotiation cluster, which turns the *clustered negotiation procedure* into the *concurrent negotiation procedure*. The detailed explanation of how to cluster an MIN is presented as follows.

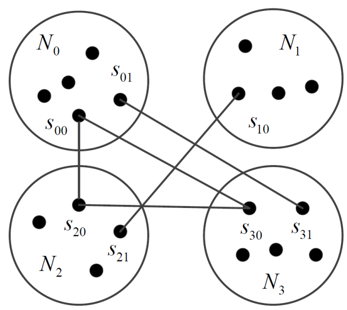

Figure 3: An example of issue interdependencies across MIN

Figure 3 shows an example of issue interdependencies across MIN. Each big circle indicates a negotiation with multiple issues, where each black dot indicates a negotiation issue, an edge between two black dots indicates an issue interdependency across MIN, and no edge between black dots indicates no issue interdependency across MIN. This example shows that there are four multi-issue negotiations in the MIN, which are Negotiations N_0, N_1, N_2, N_3, and there are three issue interdependencies across MIN, which are $s_{00} \backsim s_{20} \backsim s_{30}$, $s_{01} \backsim s_{31}$ and $s_{10} \backsim s_{21}$.

For partitioning multiple negotiations into clusters, we borrow the idea of spectral clustering [14, 18]. In this work, the "distance" between two negotiations is relevant to the *negotiation strength* between the two negotiations. The *negotiation strength* ξ_{ij} between Negotiations N_i and N_j is calculated by the number of edges between Negotiations N_i and N_j. For instance, $\xi_{01} = \xi_{13} = 0$, $\xi_{02} = \xi_{12} = \xi_{23} = 1$, and $\xi_{03} = 2$.

Algorithm 3 shows the clustered negotiation procedure for conducting MIN. In Algorithm 3, the input is a negotiation network Θ_a involving an MIN, and the output is the outcomes of all involved negotiations. The pre-calculations include: (1) Agent a calculates the negotiation strength between every two negotiations, (2) Agent a applies a clustering algorithm to partition all m negotiations into k negotiation clusters, and (3) Agent a gets the cluster sequence by sorting all negotiation clusters through calculating the importance of negotiation clusters, i.e., the sum of importance of all negotiations in a negotiation cluster (Line 3). Agent a successively conducts each negotiation cluster based on the cluster sequence. During conducting a negotiation cluster (e.g., Clu_j),

Algorithm 3: Clustered Negotiation Procedure

1 **Input:** a negotiation network Θ_a, involving an MIN.
2 **Output:** the outcomes of all negotiations in the MIN.
3 **Pre-calculations:** (1) calculate the negotiation strength between every two negotiations in the MIN, (2) use a clustering algorithm to partition all m negotiations into k negotiation clusters, and (3) sort all negotiation clusters based on the sum of importance of all negotiations in each negotiation cluster to get a cluster sequence, e.g., $Clu_0 \to \cdots \to Clu_j \to \cdots \to Clu_{k-1}$, where $\sum_{N_i \in Clu_0} \nu_i \geq \cdots \geq \sum_{N_i \in Clu_j} \nu_i \geq \cdots \geq \sum_{N_i \in Clu_{k-1}} \nu_i$, and ν_i is the importance of Negotiation N_i
4 **for** $j \leftarrow 0$ *to* $k-1$ **do**
5   concurrently conduct all negotiations in Cluster Clu_j
6   **while** *not all negotiations in Cluster* Clu_j *are completed* **do**
7   **if** *a counter-offer from its opponent in Negotiation* N_i *in Cluster* Clu_j *is received* **then**
8   retrieve all last values of issues in other negotiations which have interdependencies with issues in Negotiation N_i, and store the values in a list *lis*
9   adopt the proposed strategy in Section 3 while considering the values in the list *lis*
10   **if** *Negotiation* N_i *in Cluster* Clu_j *is completed* **then**
11   record the result of Negotiation N_0, i.e., success or failure, and calculate utility achieved in Negotiation N_i, i.e., $U(N_i)$
12   $j \leftarrow j + 1$
13 **return** the outcomes of all negotiations

Agent a concurrently conducts all involved negotiations in the negotiation cluster Clu_j (Line 5), and Agent a adopts the proposed strategy in Section 3 to negotiate with its opponents in all negotiations in the cluster Clu_j (Lines 7-9). For each completed negotiation, Agent a records the result of the negotiation and calculates the utility achieved in the negotiation (Lines 10-11). Agent a concurrently conducts all negotiations in each negotiation cluster, and conducts all negotiation clusters successively until all m negotiations are completed.

In this paper, interdependencies between issues in a single negotiation are not discussed due to well discussions in the literature. However, we adopt non-linear utility functions in this paper, which could include the case where issues in the same negotiation are interdependent. Moreover, how to generate an optimal result of clustering multiple negotiations is not the focus of this work. Therefore, the clustering optimization is not discussed in this paper.

5 EXPERIMENT

In the experiment, we simulate an agent society with various MIN scenarios, and compare the performance of the three proposed MIN procedures regarding negotiation efficiency and effectiveness.

In terms of experimental settings, we give detailed settings for single negotiations and multiple negotiations, respectively. As this paper does not focus on single negotiation level, we adopt a widely used concession strategy, an issue procedure and a negotiation protocol for agents in every single negotiation with the setting of a series of random parameters. In the experimental settings for multiple negotiations, we present different cases of MIN with the setting of various numbers of negotiations and issue interdependencies across MIN to show the performance of the three proposed MIN procedures.

5.1 Experimental Settings for Single Negotiations

In the experiment, the following "time-dependent strategy" [4] is employed as the concession strategy for agents.

$$U_a(t) = 1 - (1 - r_a)(\frac{t}{T_a})^{\frac{1}{\beta_a}} \tag{2}$$

where $U_a(t) \in [0, 1]$ denotes the utility which Agent a achieves at negotiation period t, $r_a \in [0, 1]$ is Agent a's reserved utility, T_a is Agent a's deadline and β_a indicates Agent a's concession rate.

In this work, the "package deal procedure" [6] is adopted as the *issue procedure* to process multiple issues in single negotiations, and the "alternating offer protocol" [20] is utilised for agents in single negotiations. To get general results of the proposed approach, all relevant parameters in single negotiations are randomly selected, and the details are shown in Table 1.

Table 1: Parameters in single negotiations

importance of negotiations	random
number of issues	random in $[3, 8]$
issue preference	random
deadline	random in $[10, 20]$
reserved utility	random in $[0, 3, 0.4]$
concession rate	random in $\{(0, 1), 1, (1, 3]\}$

The overall utility achieved by an agent engaged in MIN $\mathbb{N}$, represented by $U(\mathbb{N})$, can be calculated by Equation (3).

$$U(\mathbb{N}) = \sum_{\forall N_i \in \mathbb{N}} \Big(U(N_i) \times V(N_i)\Big) \tag{3}$$

where $i \geq 0$, $\mathbb{N}$ is the negotiation set, $V(N_i)$ is the result of Negotiation N_i, which is calculated by Equation (4), and $U(N_i)$ is the utility achieved by the agent in Negotiation N_i.

$$V(N_i) = \begin{cases} 0 & \text{if Negotiation } N_i \text{ is failed,} \\ 1 & \text{others.} \end{cases} \tag{4}$$

5.2 Experimental Settings for Multiple Negotiations

In the experimental settings for multiple negotiations, we take a number of MIN scenarios with various settings. In order to get general experimental results, we test the three proposed MIN procedures in two cases based on different numbers of negotiations and issue interdependencies. The detailed experimental settings in the two cases are shown in Table 2 and Table 3, respectively.

Table 2: Experimental settings for case (a)

number of negotiations	number of issue interdependencies
4	50% number of negotiations
8	
16	
30	

Table 3: Experimental settings for case (b)

number of negotiations	number of issue interdependencies
20	0% number of negotiations
	30% number of negotiations
	60% number of negotiations
	80% number of negotiations
	100% number of negotiations

Let us recall a mathematical representation of issues interdependencies shown as Equation (5) (refer to Section 2).

$$\sum_{m=l}^{n} \big(\mu_m \times o_{N_j}^{t_k}(s_m)\big) \leq Q, \tag{5}$$

where μ_m is the coefficient for the sub-offer on Issue s_m in Negotiation N_j, Q is a constant, t_k indicates a negotiation period, and $n - l + 1$ is the total number of issues involved in the issue interdependency.

The experimental settings for parameters in the mathematical representation of issue interdependencies are shown in Table 4.

Table 4: Parameters in issue interdependencies

μ_m	random in $[1, 3]$
Q	random in $[1, 5]$
$n - l + 1$	random in $[2, 5]$

In the experiment, each single MIN scenario is simulated 100 times by applying the three proposed MIN procedures. Specifically, the well-known "k-means" algorithm is employed as a clustering algorithm in the clustered negotiation procedure. Here, as this paper does not focus on the optimization of MIN procedures, we select a series of values for k in the "k-means" algorithm, and we take the average as the experimental result for the clustered negotiation procedure.

5.3 Experimental Results

In the experiment, we test the performance of three MIN procedures regarding negotiation effectiveness and efficiency, where the *agent's overall utility*, the *success rate of negotiations*, and the *number of negotiation rounds* are reported. The *agent's overall utility* indicates the overall utility achieved by an agent in an MIN, which can be calculated by Equation (3). The *success rate of negotiations* indicates the percentage of the number of successful negotiations in an MIN. The *number of negotiation rounds* indicates the total number of negotiation rounds of conducting an MIN.

The performances of three MIN procedures are tested in two cases (refer to Table 2 and Table 3), where

case (a): the number of negotiations is 4, 8, 16, 30, respectively, and the number of issue interdependencies is set as 50% the number of negotiations, and

case (b): the number of negotiations is set as 20, and the number of issue interdependencies is set as 0% the number of negotiations, 30% the number of negotiations, 60% the number of negotiations, 80% the number of negotiations, and 100% the number of negotiations, respectively.

(1) Agent's overall utility

Figure 4 shows agent's overall utility achieved by conducting three MIN procedures in **case (a)**. In Figure 4, the x-axis indicates the number of negotiations, and the y-axis indicates the overall utility achieved by the agent in the MIN. From Figure 4, it can be seen that, regardless of the number of negotiations, the concurrent negotiation procedure could achieve the highest overall utility while the successive negotiation procedure might achieve the lowest overall utility.

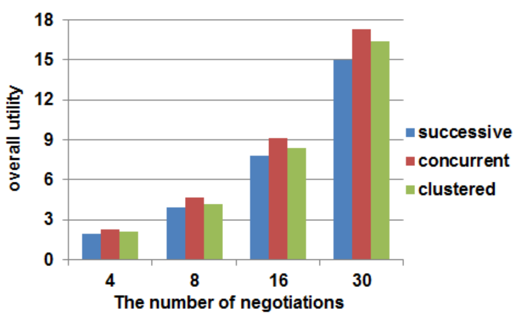

Figure 4: Agent's overall utility in case (a)

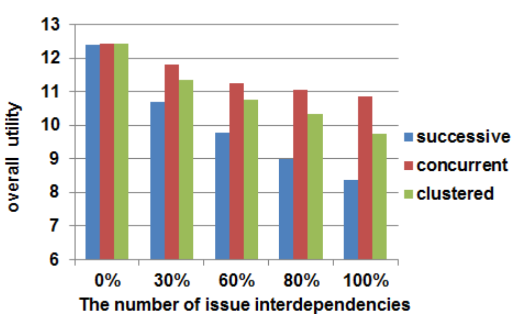

Figure 5: Agent's overall utility in case (b)

Figure 5 shows agent's overall utility achieved by conducting three MIN procedures in **case (b)**. In Figure 5, the x-axis indicates the number of issue interdependencies (e.g., "30%" indicates that the number of issue interdependencies is 30% the number of negotiations), and the y-axis indicates the overall utility achieved by the agent in the MIN. From Figure 5, it can be seen that agent's overall utility achieved in the MIN goes down with the increase of the number of issue interdependencies. Moreover, regardless of the number of issue interdependencies, the concurrent negotiation procedure could achieve the highest overall utility while the successive negotiation procedure might achieve lowest overall utility.

(2) Success rate of negotiations

Figure 6 shows the success rate of negotiations achieved

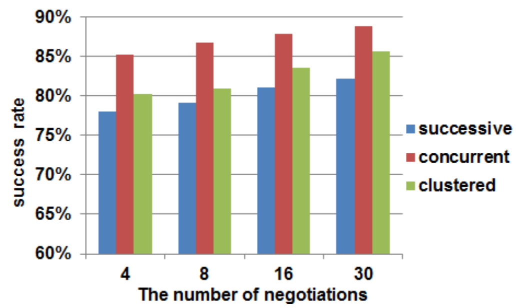

Figure 6: Success rate of negotiations in case (a)

by conducting three MIN procedures in **case (a)**. In Figure 6, the x-axis indicates the number of negotiations, and the y-axis indicates the success rate of negotiations achieved in the MIN. Figure 6 shows that, regardless of the number of negotiations, the concurrent negotiation procedure could achieve the best performance in the success rate of negotiations while the successive negotiation procedure might be the worst one.

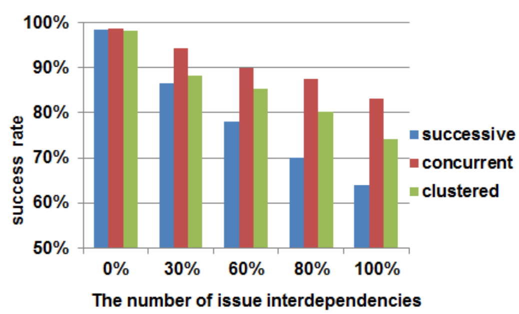

Figure 7: Success rate of negotiations in case (b)

Figure 7 shows the success rate of negotiations achieved by conducting three MIN procedures in **case (b)**. In Figure 7, the x-axis indicates the number of issue interdependencies, and the y-axis indicates the success rate of negotiations achieved in the MIN. Figure 7 shows that the success rate of negotiations goes down with the increase of the number of issue interdependencies. This is because more issue interdependencies would make fewer negotiations successful. Moreover, regardless of the number of issue interdependencies, the concurrent negotiation procedure could achieve the highest success rate of negotiations while the successive negotiation procedure might achieve the lowest success rate of negotiations.

(3) Number of negotiation rounds

Figure 8 shows the total number of negotiation rounds of

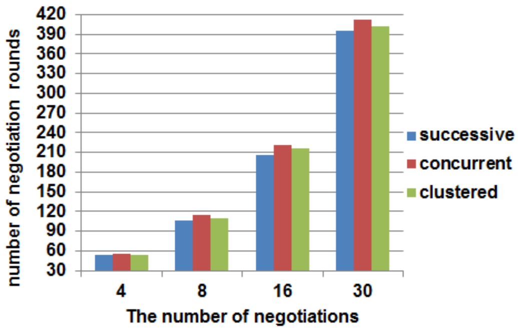

Figure 8: Number of negotiation rounds in case (a)

conducting the MIN by employing three MIN procedures in **case (a)**. In Figure 8, the x-axis indicates the number of negotiations, and the y-axis indicates the total number of negotiation rounds of conducting the MIN. Figure 8 shows that, regardless of the number of negotiations, the successive negotiation procedure could achieve the best performance in the negotiation efficiency while the concurrent negotiation procedure might be the worst one.

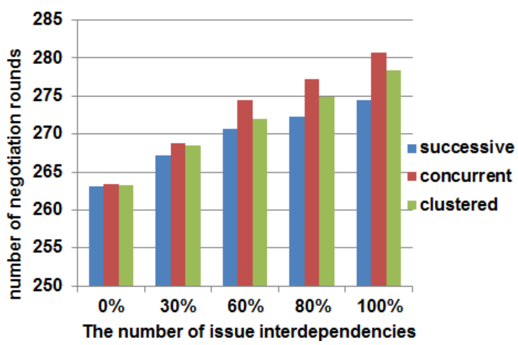

Figure 9: Number of negotiation rounds in case (b)

Figure 9 shows the total number of negotiation rounds of conducting the MIN by employing three MIN procedures in **case (b)**. In Figure 9, the x-axis indicates the number of issue interdependencies, and the y-axis indicates the total number of negotiation rounds of conducting the MIN. Figure 9 shows that the total number of negotiation rounds of conducting the MIN goes up with the increase of the number of issue interdependencies. This is because more issue interdependencies would make it more time-consuming in achieving agreements. Moreover, regardless of the number of issue interdependencies, the successive negotiation procedure could achieve the highest negotiation efficiency while the concurrent negotiation procedure might be the worst one.

In summary, the experimental results show that the proposed negotiation procedures can effectively handle MIN with various experimental settings. Regarding negotiation effectiveness, i.e., the agent's overall utility and the success rate of negotiations, the concurrent negotiation procedure could achieve the best performance. Regarding negotiation efficiency, i.e., the number of negotiation rounds, the successive negotiation procedure might be the most efficient one. However, the clustered negotiation procedure provides a well-balanced solution between negotiation effectiveness and efficiency.

6 RELATED WORK

To date, lots of negotiation approaches have been proposed in handling single negotiations. Ito et al. [10] proposed a negotiation protocol to handle multiple interdependent issues, and Hemaissia et al. [8] proposed a multilateral negotiation protocol. These approaches can only handle single negotiations with independent negotiation goals, which are powerless to handle MIN. However, our approach focuses on solving the challenges in MIN.

In the last few years, a number of concurrent one-to-many negotiation approaches [1, 15–17] are proposed in focusing on situations where an agent negotiates with other negotiators on multiple objects. These work tries to solve problems in multiple negotiations, but their main limitations are that solutions to negotiation procedures for MIN are not provided and issue interdependencies across MIN are not well considered. Niu et al. [19] proposed an approach on multiple negotiations with dependencies. However, their approach can only handle single-issue negotiation and does not provide an MIN procedure. On the contrary, this paper proposes a general MIN model, which could cover all possible negotiation scenarios, and provides three feasible MIN procedures.

So far, little work can be found in solving challenging problems in MIN, and very few solutions to negotiation procedures in processing MIN can be found. In order to cover the limitations of the previous work in MIN, this paper presents solutions to the challenges in MIN and proposes three feasible negotiation procedures for agents in processing MIN.

7 CONCLUSION

To effectively handle MIN is a challenging problem in agent negotiation. In this paper, three feasible negotiation procedures are proposed for processing MIN. With various experimental settings, an experimental analysis is given to show the performance of the three proposed negotiation procedures in conducting MIN. The experimental results show that the proposed negotiation procedures provide effective solutions to handling MIN.

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