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Reallocation Problems in Agent Societies: A Local Mechanism to Maximize Social Welfare

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Abstract

Resource reallocation problems are common in real life and therefore gain an increasing interest in Computer Science and Economics. Such problems consider agents living in a society and negotiating their resources with each other in order to improve the welfare of the population. In many studies however, the unrealistic context considered, where agents have a flawless knowledge and unlimited interaction abilities, impedes the application of these techniques in real life problematics. In this paper, we study how agents should behave in order to maximize the welfare of the society. We propose a multi-agent method based on autonomous agents endowed with a local knowledge and local interactions. Our approach features a more realistic environment based on social networks, inside which we provide the behavior for the agents and the negotiation settings required for them to lead the negotiation processes towards socially optimal allocations. We prove that bilateral transactions of restricted cardinality are sufficient in practice to converge towards an optimal solution for different social objectives. An experimental study supports our claims and highlights the impact of a realistic environment on the efficiency of the techniques utilized.

Keywords:

Resource Allocation, Negotiation, Social Welfare, Agent Society, Behavior, Emergence



Introduction

- 1.1 In the past few years, an increasing number of studies focused on resource allocation problems, either from a centralized or a distributed point of view. Optimally allocating a set of resources between agents in an artificial society is an important issue in Computer Science as well as in Economics. Indeed, numerous applications can be formulated as allocation problems in various domains ranging from auctions (Bachrach & Rosenschein, 2008; Sandholm, 2002) to industrial procurement (Giovannucci *et al.*, 2004), including grid computing (Galstyan *et al.*, 2005).
- 1.2 Centralized solving techniques only aim to determine the best way to assign resources in order to optimize the objective function, without consideration for their origin. At the opposite, distributed solving techniques consider that resources are initially allocated between agents, and the aim is to determine a sequence of transactions leading to an optimal allocation. However, most of these techniques cannot be used in practice: either they do not consider some constraints inherent to the application context or they rely on unrealistic assumptions. For instance, in many studies (e.g. Endriss *et al.*, (2006) or Chevalayre *et al.*, (2010), agents can compensate disadvantageous transactions using money from an infinite wallet. This way, any condition on a transaction can be satisfied. Similarly, relationships between agents are often not considered whereas this characteristic occurs in many applications. Indeed, agents in the population usually all know each other and can negotiate freely with each other. However, communications are often restricted in a significant number of applications (Lieberman *et al.*, 2005): business, spatial, applications based on social networks or Internet applications. Most of the time, these studies rely on omniscient agents which know everything about everybody (i.e. flawless knowledge of the whole society). However, in large-scale applications (with a large number of agents), the agents only have access to local information. Since these assumptions are not plausible from our point of view, we choose to consider a more realistic environment where agents have incomplete knowledge and limited interaction possibilities.
- 1.3 The aim of this paper is not to prove the existence of solutions with respect to a specific context (it is certainly important but not

sufficient in practice) but to propose a distributed mechanism based on agent negotiations and which can be used in a more realistic context. Our objective is to design the agent behavior and the negotiation settings to implement accordingly in order to lead the negotiation processes towards the best solutions. These solutions, which are achieved by an adaptive and anytime algorithm, can be considered as emergent.

- 1.4 This paper is structured as follows. Section 2 presents the limitations of the current studies on allocation problems. Section 3 defines some basic notions and describes what, from our point of view, is a more realistic environment. The different parameters on which relies the solving method we propose are also presented. Section 4 introduces the simulation protocol and discusses about the evaluation of agent negotiations. Characteristics favoring the achievement of socially interesting allocations are also analyzed with respect to the utilitarian and the egalitarian welfare notions. Section 7 concludes this study with a summary of the most efficient negotiation settings according to different scenarios.



Background

- 2.1 Different ways exist in the literature to evaluate the quality of resource allocations. One of them, called *social efficiency*, can be measured owing to notions from the social choice theory (Moulin, 1988; Arrow *et al.*, 2002). These notions evaluate different aspects of allocations in a global way, aggregating the satisfaction of all the agents. The average satisfaction is evaluated according to the utilitarian welfare. The egalitarian welfare focuses on the weakest satisfaction. The Nash product considers both fairness and average satisfaction while elitist societies only consider the largest satisfaction. These four welfare notions are the most important and the most widely used to date (Endriss *et al.*, 2006; Chevaleyre *et al.*, 2010; Ramezani & Endriss, 2009; Brams & Taylor, 1996) and only those will be considered in this paper for this reason.
- 2.2 The Pareto efficiency is also an omnipresent notion in the literature (Moulin, 1988; Arrow *et al.*, 2002). An allocation is Pareto-efficient if there does not exist another allocation that would increase the satisfaction of an agent without decreasing the satisfaction of any other agent. This notion is useful when agents are purely self-centered. However, in this paper, the objective is to find the best agent behavior to maximize the welfare of the agent society. Thus, selfless agents are also considered. In such a case, the Pareto efficiency appears as a less interesting notion and is not considered in this paper.
- 2.3 Many studies focusing on the different aspects of allocation problems evaluate the allocations using the welfare notions mentioned above. For instance, Sandholm, (Sandholm, 1998) establishes essential theoretical results for allocation problems in utilitarian societies. He classifies the different kinds of transaction and he also demonstrates the existence of transaction sequences leading to optimal solutions depending on the kinds of transaction allowed during negotiations. Other studies extend this theoretical work like (Endriss *et al.*, 2006; Chevaleyre *et al.*, 2010). They consider different welfare functions and design various scenarios according to many representations of agents preferences. They establish convergence results on negotiation processes according to these scenarios. Complexity of allocation problems is investigated as well. The computational complexity is analyzed to check the sufficiency of transactions involving one resource at a time in given cases (Dunne *et al.*, 2005; Dunne & Chevaleyre, 2008). These papers characterize solutions, studying the desirable properties according to different scenarios. However, these studies do not focus on the mechanism required in practice to achieve a solution maximizing the welfare of a society. These studies are based on omniscient agents that can negotiate without restrictions. Only self-centered agents are considered and collaboration is meaningless.
- 2.4 In (Chevaleyre *et al.*, 2007), authors study the allocation of goods to eliminate envy within a population. They establish convergence and complexity results on graph allocation problems. The authors do not consider the agent behaviour to implement in order to achieve optimal solutions in practice. Task allocation problems are also studied when communication abilities between agents are restricted (de Weerd *et al.*, 2007). The authors only consider the utilitarian perspective of the problem and propose some exponential algorithms. Simulations are performed on random graphs of different kinds (small-world, scale-free, ...). Some authors focus on topological issues, where the behaviour and the performance of complex systems are studied according to topological characteristics (Dekker, 2007)). Instead of studying allocation problems in a generic way, some authors focus on a specific game, e.g. the ultimatum game, and study the evolution of fairness on complex networks (Xianyu, 2010). Some studies focus on dynamic populations. For instance, (Zoethout *et al.*, 2010) studies the impact of a newcomer on the efficiency and the performance according to different scenarios. The authors use different performance indicators that can be compared to social measures. The time performance of the slowest agent corresponds to an egalitarian metric whereas the sum of the individual performances of all the agents (the labour cost) corresponds to an utilitarian point of view. In this paper, the environment is static: the size of the artificial society and the total number of resources do not vary.



Multiagent resource allocation problem

- 3.1 In this section, resource allocation problems are defined and characterized according to several crucial parameters. We describe our claim for a more realistic environment and we discuss about its importance and its impact on the efficiency of solving techniques. Different elements on which our agent-based solving method relies are finally described (Nongillard *et al.*, 2008). All the concepts are defined in such a way that their distributed implementation is facilitated.

Basic notions

- 3.2 Allocation problems are usually defined based on a population of agents and on a set of resources. The agents express their preferences on all the resources and have a bundle containing their own resources. The aim of resource allocation problems is to find an allocation, i.e. an assignment of the set of resources between the agents of the population, maximizing (or minimizing) a given objective.
- 3.3 Several parameters affect the properties of an allocation problem. Even a slight difference between the characteristics of two allocation problems can have a fundamental impact on the way these problems can be solved efficiently. One of these crucial parameters is the nature of the resources considered. It affects directly the properties of resource allocations.
- 3.4 In this paper, resources are assumed atomic, not shareable and unique. Since resources are assumed *atomic*, agents cannot divide them in order to trade only a part. For instance, a book is an atomic resource: trading it page by page is impossible. Resources are *not shareable* which means the satisfaction of an agent only depends on the resources in its bundle, i.e. resources that belong to another agent cannot be considered in the evaluation of the satisfaction of the agent. Finally, resources are *unique* and tagged with a unique identification number. Such an environment is called *single-unit* (in contrast with a multi-unit environment where several similar resources cannot be distinguished). For instance, let us consider a box of 8 eggs. It is possible either to consider the whole box as an atomic resource or to consider each egg as a resource. In the latter case, owning the first egg of the box is not equivalent to owning the last one. Both cases correspond to two different resource allocations.
- 3.5 According to these characteristics, a resource allocation can be defined more formally as follows:

Definition 1 (Allocation) Given a set \mathcal{R} of m resources and a population \mathcal{P} of n agents, a resource allocation A is an ordered list of n resource bundles $R_i \subseteq \mathcal{R}$ describing the resources owned by each agent i .

$$A = [R_1, \dots, R_n], \quad 1, \dots, n \in \mathcal{P}, \quad A \in \mathcal{A}.$$

where \mathcal{A} is the set of all possible allocations. A resource allocation also satisfies the following properties:

$$\bigcup_{i \in \mathcal{P}} R_i = \mathcal{R}, \quad \bigcap_{i \in \mathcal{P}} R_i = \emptyset, \quad \text{and} \quad A(i) = R_i, \quad i \in \mathcal{P}.$$

In other words, an allocation is constituted by the ordered list of the agent bundles. Moreover all the resources must be allocated to the agents and a resource can only belong to one agent at a time.

- 3.6 As described in Section 1, this paper focuses on distributed methods based on agent negotiations according to a more realistic context. We assume the knowledge of an agent is incomplete: an agent only knows its preferences, its bundle of resources and a list of neighbors (agents with which interactions are possible). This way, each agent is able to negotiate with the restricted number of agents formed by its neighborhood. The agents also negotiate according to a given policy: the transactions they use for trading resources belong to a given set. A negotiation problem can thus be defined more formally as follows:

Definition 2 (Negotiation problem) A negotiation problem is a tuple $\langle \mathcal{P}, \mathcal{R}, \Delta, \mathcal{G} \rangle$, where $\mathcal{P} = \{1, \dots, n\}$ is a finite population of n agents, $\mathcal{R} = \{r_1, \dots, r_m\}$ is a finite set of m resources, Δ is a set containing the kinds of transaction allowed during the negotiations, and \mathcal{G} is the contact graph.

- 3.7 Restrictions on the communications between agents are modeled by a contact graph \mathcal{G} where the nodes represent the agents and the edges represent the interaction possibilities between the agents so that two agents linked in the graph can negotiate together. Note that in practice this graph is distributed among the agents of population \mathcal{P} as agent neighborhoods.

Definition 3 (Contact graph) A contact graph is an undirected graph $\mathcal{G} = (\mathcal{P}, \mathcal{E})$. Two agents can communicate if an edge from \mathcal{E} between them exists. Note that this relation is symmetric.

- 3.8 An agent can be defined in a generic way by a resource bundle, a valuation function describing its preferences, a list of agents (also called neighbors) with which it is able to communicate, a behavior describing how it negotiates with others and an acceptability criterion related to its decision-making.

Definition 4 (Agent) An agent $i \in \mathcal{P}$ is a tuple $\langle R_i, v_i, B_i, C_i, N_i \rangle$, where R_i is the set of m_i resources the agent owns, v_i is the valuation function (the agent preferences), N_i is the list of n_i neighbors, B_i defines the agent behavior according to which the agent negotiates, and C_i is its acceptability criterion on which is based its decisions.

Example 1 Figure 1 illustrates a negotiation problem based on a population of 6 agents and a set of 9 resources ($\mathcal{P} = \{1, \dots, 6\}$, $\mathcal{R} = \{r_1, \dots, r_9\}$).

These resources are initially allocated to the agents. Each agent owns a resource bundle and their aggregation constitutes the initial resource allocation, which can be extracted from Figure 1 as follows:

$$A = \left[\{r_3\} \{r_1, r_4, r_5\} \{r_6, r_9\} \{r_7, r_8\} \{\} \{r_2\} \right].$$

According to allocation A , agent 1 only owns r_3 while agent 2 owns 3 resources r_1, r_4 and r_5 . No resource belongs to agent 5, etc...

The contact graph describes the interaction possibilities of the agents. Two agents can only communicate if they are directly linked. According to the topology of the contact graph described in Figure 1, we can say that agent 4 is able to negotiate with agents 2 and 6 while agent 3 can only communicate with agent 1.

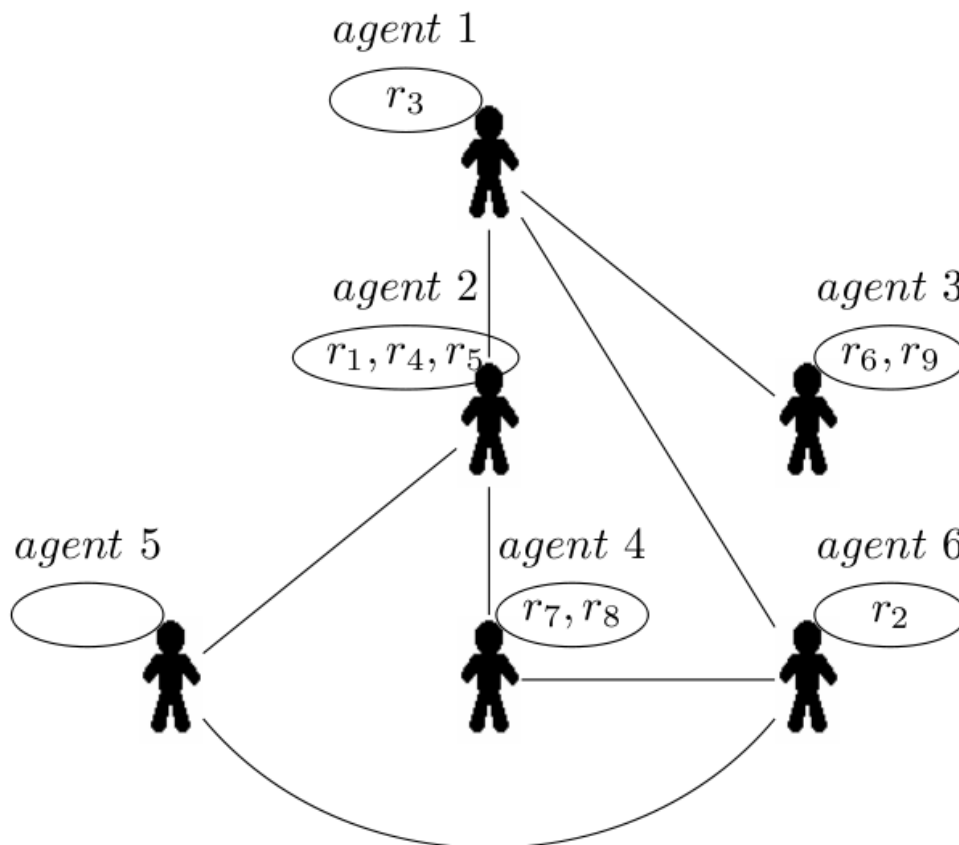


Figure 1: An example of negotiation problem

Considering a centralized technique, the resources and the agent preferences are gathered in a central entity which determines an optimal resource distribution performed afterwards. However, considering a distributed method based on agent negotiations, the solving process proceeds as follows. An agent is selected to be the initiator, agent 1 for instance. It negotiates in its neighborhood by first selecting one neighbor, agent 2 for instance, and then negotiating with it according to its behavior. They both locally determine that the exchange of resources r_3 and r_5 is acceptable, with respect to their own criterion. This transaction is performed and the resource allocation evolves. A new initiator is selected and the process continues until no more acceptable transaction can be determined.

3.9 Many applications can be modeled using such a representation. For instance, home exchange websites which appear on the Internet. Each customer/agent enters the system with one resource: its house. They want to exchange their house for another one during a given time period (for holidays for example). The contact graph can be built out of the customers requirements. The objective of such an application is to satisfy a maximum number of customers without neglecting any of them (every customer who lend their house must find another one in return). The next section is dedicated to another crucial model parameter: the evaluation of an allocation from a local and a global point of view. The importance and the impact of using a contact graph is also discussed.

Individual and collective welfare

- 3.10 The satisfaction of an agent depends directly on its personal resources. It can be evaluated by a *valuation function* considering different parameters more or less important to the agent.
- 3.11 In many studies in the literature, the individual welfare of an agent (i.e. its satisfaction) only depends on its utility (Endriss *et al.*, 2006; Chevaleyre *et al.*, 2010; Sandholm, 1998). In such studies, money is introduced during the transactions. Indeed, transactions are performed if and only if they satisfy all the conditions imposed by all the agents involved in the transaction. Money can be used to compensate a disadvantageous transaction leading to a loss of utility for example. One constraint only controls the use of money: it prevents the creation of money during a transaction. In other words, the amount of money given by an agent (negative value) corresponds to the exact amount of money received by the other agent (positive value). The sum of compensatory payments of a transaction must be null. This argument seems consistent and reasonable. However, it is not sufficient and it leads to unrealistic situations since the agent wallet is not bounded. An agent is considered as rich as required to compensate any disadvantageous transaction. Infinite compensatory payments do not represent a plausible assumption in most applications. Instead of allowing infinite compensatory payments, we choose not to consider money and to restrict the valuation function to a *utility function* in this paper.
- 3.12 Various representations of agent preferences exist in the literature (Doyle, 2004; Mas-Colell *et al.*, 1995). In this paper, agents express their preferences using a cardinal quantitative representation: an additive utility function.

Definition 5 (Utility function) An agent evaluates its individual welfare using an additive utility function $u_i : 2^{\mathcal{R}} \rightarrow \mathbb{R}$. When agent $i \in \mathcal{P}$ owns a set of resources $R_i \subseteq \mathcal{R}$, its utility is evaluated as follows:

$$u_i(R_i) = \sum_{r \in R_i} u_i(r), \quad i \in \mathcal{P}, \quad R_i \subseteq \mathcal{R}.$$

Example 2 Let us illustrate the evaluation of the individual welfare using a simple example, based on a population of 3 agents $\mathcal{P} = \{1, 2, 3\}$ and a set of 6 resources $\mathcal{R} = \{r_1, \dots, r_6\}$. The agents preferences are described in Table 1. According to this table, agent 1 associates with resource r_2 the utility value: $u_1(r_2) = 7$.

Table 1: Individual Welfare – Agent preferences

$u_i(r_j)$		Resource Set \mathcal{R}					
		r_1	r_2	r_3	r_4	r_5	r_6
Population \mathcal{P}	1	10	7	10	9	2	1
	2	6	10	3	4	8	6
	3	1	2	1	2	1	3

If the initial resource allocation is $A = [\{r_4\}, \{r_1, r_2, r_6\}, \{r_3, r_5\}]$, then the utility of all the agents can be easily computed as follows:

$$u_1(R_1) = u_1(\{r_4\}) = u_1(r_4) = 9$$

$$u_2(R_2) = u_2(\{r_1, r_2, r_6\}) = u_2(r_1) + u_2(r_2) + u_2(r_6) = 6 + 10 + 6 = 22$$

$$u_3(R_3) = u_3(\{r_3, r_5\}) = u_3(r_3) + u_3(r_5) = 1 + 1 = 2$$

- 3.13 The individual welfare is the evaluation of an allocation from an agent point of view thanks to its utility function. The quality of an allocation must be evaluated from a global point of view. In this purpose, notions from the social choice theory are usually used (Moulin, 1988; Arrow *et al.*, 2002). These notions aggregate the satisfaction of all agents in the population to evaluate an allocation. In this paper, we focus on the four most important notions.
- 3.14 The most widely used notion is the utilitarian welfare, which optimizes the average satisfaction in a population.

Definition 6 (Utilitarian welfare) The utilitarian welfare of a resource allocation A corresponds to the sum of individual welfare.

$$sw_U(A) = \sum_{i \in \mathcal{P}} u_i(R_i), \quad A \in \mathcal{A}.$$

- 3.15 The egalitarian welfare of an allocation corresponds to the individual welfare of the poorest agent in the population. Its maximization tends to reduce inequalities in the societies.

Definition 7 (Egalitarian welfare) The egalitarian welfare of an allocation A corresponds to the individual welfare of the poorest agent.

$$sw_e(A) = \min_{i \in \mathcal{P}} u_i(R_i), \quad A \in \mathcal{A}.$$

- 3.16 The Nash product considers the average individual welfare and the inequalities within an agent population. This notion can be viewed as a compromise between the utilitarian and the egalitarian welfare. This notion is independent of utility scales and it also normalizes the agents utility. However this notion becomes meaningless if non-positive values are used.

Definition 8 (Nash product) The Nash product of an allocation A corresponds to the product of individual welfare.

$$sw_n(A) = \prod_{i \in \mathcal{P}} u_i(R_i), \quad A \in \mathcal{A}.$$

- 3.17 Finally, the elitist welfare only considers the welfare of the richest agent in the population. This notion can be useful in the context of artificial societies for instance, where agents have a common objective. This objective must be fulfilled irrespective of the agent which achieves it.

Definition 9 (Elitist welfare) The elitist welfare of an allocation A corresponds to the individual welfare of the richest agent in the population.

$$sw_e_l(A) = \max_{i \in \mathcal{P}} u_i(R_i), \quad A \in \mathcal{A}.$$

- 3.18 All the basic notions having been presented, we can use them to discuss the importance of the social graph in the next section.

Importance of the contact graph

- 3.19 Since only few studies consider restrictions on agent interactions, it is legitimate to investigate the importance of such a parameter. Indeed, negotiation processes, which lead to optimal solutions according to complete communication possibilities (i.e., based on complete social graphs), may only lead to solutions far from the optimum when communications are restricted.

Proposition 1 (Social graph impact) *Independently of the objective function considered, a restricted social graph may prevent the achievement of optimal resource allocations.*

Proof. Let us prove this proposition by a counter-example based on a population $\mathcal{P} = \{1, 2, 3\}$ and a set of resources $\mathcal{R} = \{r_1, r_2, r_3\}$. The objective is to maximize the Nash welfare. All the agents are assumed self-interested (they only accept transactions increasing their own individual welfare). The agent preferences are described in Table 2 while the contact graph, which describes the interaction possibilities, is represented in Figure 2.

Table 2: Contact graph impact – Agent preferences

$u_i(r_j)$		Resource Set \mathcal{R}		
		r_1	r_2	r_3
Population \mathcal{P}	1	3	1	9
	2	1	4	1
	3	10	2	3

According to the topology of this social graph, agent 2 can communicate with agents 1 and 3, while they can only communicate with agent 2 but not together. The initial resource allocation is $A = [\{r_1\}\{r_2\}\{r_3\}]$ and is associated with $sw_n(A) = 36$.

agent 1 agent 2 agent 3



Two resource swaps (one-for-one resource replacement) only are possible. Agents 1 and 2 can exchange r_1 and r_2 or agents 2 and 3 can exchange respectively r_2 and r_3 . Both cases lead to a decrease of the utility of at least one participant. Thus, no acceptable exchange is possible here.

However, allocation A is not an optimal solution. Indeed, the swap of r_1 and r_3 by agents 1 and 3 would lead to a better allocation $A' = [\{r_3\}\{r_2\}\{r_1\}]$, which is associated with $sw_n(A) = 360$. Hence, due to the topology of the social graph restricting the interaction possibilities, the negotiation process cannot achieve an optimal solution. \square

- 3.20 Considering the social graph also has an indirect influence on negotiation processes. While it may not be important to consider the order in which the agents negotiate when the social graph is complete, this order becomes essential when communications between agents are restricted. Indeed, if restrictions on agent communications are not considered, resources can always be traded with all other agents.

Proposition 2 (Negotiation order) *Independently of the objective function considered, the order in which agents negotiate with each other may prevent the achievement of optimal resource allocations.*

Proof. The proposition can be proved by a counter-example. Let us consider a population $\mathcal{P} = \{1, 2, 3\}$ of selfish agents and a set of resources $\mathcal{R} = \{r_1, r_2, r_3\}$. The objective is still to maximize the Nash welfare. The agent preferences are described in Table 3 and the contact graph is illustrated in Figure 2. The initial resource allocation is $A = [\{r_1\}\{r_2\}\{r_3\}]$ with $sw_n(A) = 6$.

Table 3: Negotiation order – Agent preferences

$u_i(r_j)$		Resource Set \mathcal{R}		
		r_1	r_2	r_3
Population \mathcal{P}	1	2	10	4
	2	5	3	9
	3	2	7	1

Let us now assume that agent 2 initiates a negotiation. According to the topology, two partners are possible. Depending on the choice of the initiator, the negotiation process may end on a sub-optimal allocation. Indeed, if agent 2 negotiates first with agent 1, the allocation achieved is $A' = [\{r_2\}\{r_1\}\{r_3\}]$ with $sw_n(A) = 50$. However, if agent 3 is chosen first, the allocation achieved is $A'' = [\{r_1\}\{r_3\}\{r_2\}]$ with $sw_n(A'') = 126$.

Hence, the order of negotiation becomes an important parameter to consider when the interaction possibilities are restricted. \square

- 3.21 In this section, we have shown the importance of considering restricted communication abilities, as it occurs in many applications. These restrictions represent more plausible assumptions but they also have important consequences for the negotiation efficiency. The topological characteristics may prevent the achievement of optimal solutions. Moreover, the order in which agents negotiate may also lead negotiation processes to sub-optimal allocations. In spite of their respective impact, these two parameters have not been considered so far. The context of many former studies can be considered as ideal while ours is more realistic.
- 3.22 A negotiation process between agents changes an initial resource allocation to an optimal one using local transactions. Agents only accept transactions that satisfy their acceptability criterion. When no agent is able to find an acceptable transaction with respect to its behavior then the negotiation process is considered as over. The next section describes the transactions and the different acceptability criteria.

- 3.23 During a negotiation process, the resource allocation evolves step by step by means of local transactions between agents. The resource traffic is generated by these transactions as they move resources successively from the bundles of one agent to another. Transactions can be classified in two main families (Sandholm, 1998): *multilateral transactions* where many agents can be involved simultaneously and *bilateral transactions* where only two agents at a time can trade resources. Although a few studies are dedicated on multilateral transactions (Endriss & Maudet, 2005), no algorithm exists to determine them in a scalable way. Consequently, only bilateral transactions are considered in this paper.
- 3.24 Two agents at a time are involved in bilateral transactions: an initiator and its partner. Bilateral transactions can be characterized by the number of resources that both participants can propose. Thus, it can be defined in a generic way as follows:

Definition 10 (Bilateral transactions) A bilateral transaction between two agents $i, j \in \mathcal{P}$, denoted by δ_i^j , is initiated by agent i and involves a partner agent j . It is a pair $\delta_i^j(u, v) = (\rho_i, \rho_j)$, where the initiator i offers a set ρ_i of u resources and its partner j offers a set ρ_j of v resources.

A transaction δ transforms an initial allocation A into a new allocation A' . Different notations exist in the literature to express such an evolution using the state of the system before and after the transaction, like $\delta = (A, A')$ for instance. All bilateral transactions classified in (Sandholm, 1998) can be represented using the model presented in Definition 10. For instance, a $\langle 1, 0 \rangle$ -transaction corresponds to a gift (also called *O-contract*): the initiator gives a unique resource without counterpart.

- 3.25 The complexity of a negotiation between two agents is significantly affected by the maximum number of resources the agents are willing to offer.

Proposition 3 (Bilateral complexity) *The number of possible bilateral transactions between two agents $i, j \in \mathcal{P}$ where exactly u and v resources can be respectively offered is:*

$$\#\delta_i^j = \binom{m_i}{u} \times \binom{m_j}{v}.$$

- 3.26 The kinds of transaction allowed during a negotiation, denoted by Δ , define a negotiation policy. For instance, the agents may also be allowed to offer resources in a transaction up to a specified amount. Let us call "up to $\langle 2, 2 \rangle$ " the negotiation policy according to which the agents can offer either nothing, one or two resources. The kinds of transaction allowed can be written explicitly as:

$$\text{"up to } \langle 2, 2 \rangle \text{"} \Leftrightarrow \Delta = \{ \langle x, y \rangle \mid x \leq 2, y \leq 2 \}$$

Proposition 4 (Complexity of Negotiation policy) *If the two agents $i, j \in \mathcal{P}$ are allowed to offer up to u' and v' resources ($u' \leq m_i, v' \leq m_j$) then the number of possible bilateral transactions between them is:*

$$\#\delta_i^j = \left(\sum_{x=0}^{u'} \binom{m_i}{x} \right) \left(\sum_{x=0}^{v'} \binom{m_j}{x} \right) - 1.$$

Proof. A negotiation policy is defined based on the number of resources an agent can offer. If an agent can offer up to three resources then it can offer any subset of his bundle containing at most three resources. $\binom{k}{m_i}$ represents the possible number of offers containing exactly k resources that agent i can propose (according to the number of resources it owns m_i). The total number of offers an agent can propose can be computed by a simple summation of such terms. Once the number of offers has been computed for each agent, determining the possible number of transactions between them is trivial. \square

Example 3 For instance, let us consider two agents $i, j \in \mathcal{P}$ involved in a negotiation initiated by agent i . These agents own bundles of respectively 10 and 20 resources. Let us determine the possible number of transactions according to different negotiation policies.

$$\Delta = \{ \langle 1, 0 \rangle \} \Rightarrow \#\delta_i^j = 10$$

$$\Delta = \{ \langle 1, 1 \rangle \} \Rightarrow \#\delta_i^j = 199$$

$$\Delta = \{ \langle x, y \rangle \mid x \leq 2, y \leq 2 \} \Rightarrow \#\delta_i^j = 40500$$

When only gifts from the initiator are allowed, 10 transactions are possible since the agent owns 10 resources only. When swaps only are allowed, both participants offer one unique resource. Thus, 200 different transactions are possible. However, when

participants can offer up to two resources from their bundle, the number of possible transactions explodes up to 40,500. According to the kinds of transaction allowed, a negotiation can quickly become unscalable. Restricting the cardinality of the allowed transactions is thus essential to guarantee the scalability of the solving method.

- 3.27 In a distributed environment where agents have only access to local information, the finiteness of the solving process is essential. It can be guaranteed by the use of a proper acceptability criterion, enabling the agents to locally determine the profitability of a transaction. When no agent is able to find an acceptable transaction in its neighborhood, the negotiation process stops. The most widely used criterion is the *individual rationality* (Camerer, 2003; Sandholm, 1998; Montet & Serra, 2003). Since no compensatory payment is allowed, a rational agent only accepts transactions that increase its individual welfare. This notion can be defined as follows:

Definition 11 (Individually rational agent) A rational agent accepts only transactions δ which change an initial allocation A into another one A' while increasing its individual welfare:

$$u_i(R_i') > u_i(R_i), \quad i \in \mathcal{P}.$$

In (Endriss *et al.*, 2006), the notion of *cooperative rationality* has been introduced. The authors proved that any sequence of cooperative rational transactions leads to Pareto optimal allocations. However, Pareto optimal allocations can be far from socially optimal allocations. Moreover, the notion of cooperative rationality cannot be used easily in practice. Indeed, a weak inequality may lead to a cycle of transactions between equivalent allocations, which can prevent the convergence of the negotiations. Thus, the negotiation processes between cooperative rational agents may not be finite.

- 3.28 The individual rationality guarantees that the welfare of each agent is increased by each transaction. However, from the point of view of the society, negotiations between individually rational agents may also lead to severely sub-optimal allocations. As a consequence, a different acceptability criterion should be used to achieve better allocations society-wise. We propose the notion of *social agents* which are willing to accept transactions that decrease their individual welfare as long as they favor the welfare of the whole society.

Definition 12 (Social agent) A social agent only accepts transactions $\delta(A) = A'$ that do not penalize the whole society.

$$sw(A) \geq sw(A'), \quad A, A' \in \mathcal{A}.$$

- 3.29 This definition is close to the definition of individually rational agents in (Endriss *et al.*, 2006) when compensatory payments are allowed. However, the different context leads to drastic changes in its practical use. Firstly, this criterion is based on global knowledge which is not available at the agent level (the resource allocation). Secondly, the use of a weak inequality may lead to infinite negotiation processes like in the case of *collaborative rationality* described previously.
- 3.30 The formal definition of this social acceptability criterion is based on global information. However, we assume that the knowledge of the agents is restricted to their own preferences, their own bundle or information that can be collected during a negotiation (from related agents involved in the current transaction only). That way, an agent is neither aware of the current resource assignment nor of the population size and the preferences of the other agents. Consequently, an agent does not have enough information to determine the social welfare value, although computing the social welfare value is not essential. Indeed, an agent merely needs to know whether the transaction increases or decreases the social welfare value. The expression of the social acceptability criterion can be restricted to the transaction participants. Of course, the formula of the acceptability criterion must be adapted with respect to the social notion considered, as described in the next paragraphs. These restricted criteria are strict inequalities in order to guarantee the finiteness of the negotiation processes.

Utilitarian sociability

- 3.31 Social agents accept transactions that do not harm the society, even if they decrease their individual welfare. Let us adapt the generic formula to the specific case of utilitarian societies (Nongillard *et al.*, 2008). An utilitarian transaction $\delta^j = (\rho_i, \rho_j)$, which transforms A in A' ($A, A' \in \mathcal{A}$), must satisfy the following condition:

$$sw_u(A) < sw_u(A')$$

$$u_i(R_i) + u_j(R_j) + \sum_{k \in \mathcal{P} \setminus \{i, j\}} u_k(R_k) < u_i(R_i') + u_j(R_j') + \sum_{k \in \mathcal{P} \setminus \{i, j\}} u_k(R_k')$$

$$u_i(R_i) + u_j(R_j) < u_i(R_i') + u_j(R_j')$$

$$u_i(R_i) + u_j(R_j) < u_i(\rho_i) + u_j(\rho_j) - u_i(\rho_i) + u_j(\rho_j) - u_j(\rho_j)$$

$$u_i(\rho_i) + u_j(\rho_j) < u_i(\rho_i) + u_j(\rho_j)$$

In other words, if the partner associates a larger utility value with the resources offered than the initiator, then the transaction is profitable to the society. Each utilitarian transaction leads to a strict increase of the welfare of the society (if utility values are not null). Note that the utilitarian interpretation of the social acceptability criterion is only based on the resources offered. The initial individual welfare of the participants does not affect the acceptability of a transaction.

Egalitarian sociability

- 3.32 In the case of an egalitarian society, transactions reduce inequalities between agents. A fair transaction $\delta_i^j = (\rho_i, \rho_j)$, which transforms A in $A(A, A \in \mathcal{A})$, must satisfy the following conditions:

$$\begin{aligned} sw_e(A) &\leq sw_e(A) \\ \min_{k \in \mathcal{P}} (u_k(R_k)) &\leq \min_{k \in \mathcal{P}} (u_k(R_k')) \\ \min_{i, j \in \mathcal{P}} (u_i(R_i), u_j(R_j)) &< \min_{i, j \in \mathcal{P}} (u_i(R_i'), u_j(R_j')) \end{aligned}$$

The poorest agent after a fair transaction must be richer than the poorest agent before the transaction. When the egalitarian welfare is considered, an increase of the welfare value cannot be guaranteed. Indeed, depending whether or not the poorest agent is involved in the transaction, the egalitarian welfare value may not be increased. If the poorest agent is not involved, its utility value, which corresponds to the egalitarian welfare value, does not vary since its resource bundle is not modified. Thus, the egalitarian welfare value only changes if the poorest agent of the population is involved. In contrast to the utilitarian acceptability criterion, which only depends on the traded resources, the egalitarian interpretation is based on the sets of traded resources as well as on the initial individual welfare of each participant. According to such a criterion, a very rich agent may accept to decrease its own utility for the benefit of the whole society. In the case where the poorest agent is not involved in a transaction, the egalitarian criterion favors the resource traffic.

Nash sociability

- 3.33 The Nash welfare can be viewed as a compromise between the utilitarian and the egalitarian notions. The Nash interpretation of the social acceptability criterion also combines the characteristics of both notions (Nongaillard *et al.*, 2010; Nongaillard *et al.*, 2009). A Nash transaction $\delta_i^j = (\rho_i, \rho_j)$, which transforms A in $A(A, A \in \mathcal{A})$, must satisfy the following condition:

$$\begin{aligned} sw_n(A) &< sw_n(A) \\ \prod_{k \in \mathcal{P}} u_k(R_k) &< \prod_{k \in \mathcal{P}} u_k(R_k') \\ u_i(R_i) u_j(R_j) \prod_{k \in \mathcal{P} \setminus \{i, j\}} u_k(R_k) &< u_i(R_i') u_j(R_j') \prod_{k \in \mathcal{P} \setminus \{i, j\}} u_k(R_k') \\ u_i(R_i) u_j(R_j) &< u_i(R_i') u_j(R_j') \end{aligned}$$

Each Nash transaction strictly improves the welfare of the society, like in utilitarian transactions. Similarly to the egalitarian interpretation of the social acceptability criterion, the Nash criterion must be based on traded resources as well as on the individual welfare of both participants.

Elitist negotiations

- 3.34 Elitist agents accept transactions $\delta_i^j = (\rho_i, \rho_j)$, changing A into $A(A, A \in \mathcal{A})$, if the following condition is satisfied:

$$\begin{aligned} sw_e(A) &< sw_e(A) \\ \max_{k \in \mathcal{P}} (u_k(R_k)) &\leq \max_{k \in \mathcal{P}} (u_k(R_k')) \end{aligned}$$

$$\max_{i,j \in \mathcal{P}} (u_i(R_i), u_j(R_j)) < \max_{i,j \in \mathcal{P}} (u_i(R_i'), u_j(R_j'))$$

The richest of the two participants after an elitist transaction must be richer than the richest agent before this transaction. Similarly to the egalitarian interpretation, an increase of the elitist welfare value cannot be guaranteed. However, the restriction is not as strong as the restriction imposed in the egalitarian case. Indeed, if the poorest agent of the population is not involved, the egalitarian welfare value cannot vary, but according to the elitist notion, even if the richest agent is not involved, the welfare value can increase. Nothing prevents for instance another agent to become richer than the agent that was the richest before the transaction.

Agent behaviors

- 3.35 A behavior defines an agent from an external point of view: it describes how an agent interacts with others, i.e. how they negotiate. A transaction is a combination of offers from each participant. An agent initiating a negotiation selects a partner from its neighborhood, makes and receives offers and checks their acceptability according to its own criterion. If a transaction is acceptable for every participant, it is performed. Otherwise, one agent must modify its offer, in accordance with its behaviour, and the negotiation continues. The order in which these actions are performed (if they are) constitutes a behavior.
- 3.36 Many behaviors have been implemented and tested but only the most efficient (according to the quality of the solutions achieved) is presented here (Nongillard *et al.*, 2008). Our experiments show that agents should be able to change their offers and partners. Such a behavior is more time-consuming than stubborn behaviors (agents refuse to change their offers) but leads negotiation processes to higher social welfare values. The order in which the actions are performed according to a behavior also affects the efficiency of the negotiations. Three levels of priority can be distinguished: on the partner selection, on initiator offers and on partner offers. Our experiments show that the behavior described next is the most efficient.
- 3.37 According to the kinds of negotiation policy allowed, each agent can offer up to a maximum number of resources. Doing so, they generate a list of the offers they can make according to their preferences and they sort it. Agents always propose the least penalizing offer first. In this behavior called *frivolous flexible*, described in Algorithm 1, the offer and the partner can be changed by the initiator during a negotiation. Each offer is proposed to every neighbor by the initiator first of making a concession and modifying the offer.

Algorithm 1: Frivolous and flexible agent behavior

```

Data: Agent initiator  $i$ 

// generates its offer list according to its policy
 $\mathcal{L}_i \leftarrow$  generates  $(\Delta, R_i)$  ;
// sorts its offer list to propose first cheapest one
Sorts  $\mathcal{L}_i$  according to  $u_i$  ;
// Mix the neighborhood to avoid selection bias
Shuffles  $N_i$  ;
// Third priority on initiator offers
forall  $\rho_i \in \mathcal{L}_i$  do
    // Second priority on the partner selection
    forall  $j \in N_i$  do
        // First priority on partner offers
        forall  $\rho_j \in \mathcal{L}_j$  do
            // Transaction creation
             $\delta_i^j \leftarrow (\rho_i, \rho_j)$  ;
            if ACCEPTABILITY TEST then
                Performs  $\delta_i^j$  ;
                Ends the negotiation ;

```

- 3.46 Note that when the utilitarian welfare is considered, the three priorities do not affect the results. Indeed, different negotiation processes will lead to equivalent solutions. However, when other welfare notions are considered, these priorities, which define the order of the actions, can lead to suboptimal allocations.



Simulation results

- 4.1 This section starts with detailing how negotiation processes are evaluated, presenting the metrics used and their role. Then, the experimental protocol is described to present what simulations have been performed. Only simulations related to utilitarian and egalitarian societies are analyzed in the next sections.

Evaluation metrics

- 4.2 In this experimental study, different aspects of negotiation processes are evaluated by to three main parameters.
- 4.3 The first parameter is the *transaction cardinality*. Identifying an acceptable bilateral transaction may become a complex and expensive task if large numbers of resources can be traded at once, as described in Section 3.4. In order to favor the scalability of our method, restrictions on the transaction cardinality are essential. However, such restrictions may affect the efficiency of negotiation processes. The aim is to determine if the use of large transactions is necessary to achieve socially interesting allocations.
- 4.4 The second parameter we use to evaluate negotiation processes is the *social efficiency*. Although resource allocation problems can be solved using a centralized framework, a solution provided by such a technique merely allocates the resources optimally, without considering the transaction sequence required to achieve it. Such approaches cannot handle restricted graphs in a scalable way. An omniscient central entity gathers every information, from bundles to agents preferences, in order to determine the optimal outcome. Social welfare values provided by such centralized techniques can be used as references to evaluate the absolute efficiency of our distributed mechanism. The centralized techniques used to estimate the optimal value are described at the beginning of each result section.
- 4.5 The topological characteristics of a contact graph have a direct impact on the efficiency of negotiation processes. For this reason, contact graphs from different classes are considered in order to evaluate the negotiation processes on representative graphs. We focus on a specific parameter: the *mean connectivity*. The mean connectivity corresponds to the average number of neighbors per agent and therefore represents the density of the contact graph. The aim is here to determine the size of the neighborhood required to achieve socially efficient allocations.

Simulation protocol

- 4.6 Having defined how negotiation processes are evaluated, let us now describe how the simulations are performed.
- 4.7 Each experiment is set up as follows. An artificial society is composed of 50 agents ($n = 50$) and 250 resources ($m = 250$) spread between them. Two types of structured graph (complete and grid) and two types of random graph (Erdős-Rényi 1959) and small world (Albert & Barabási 2002) are considered. First of starting the experiment, a large number of scenarios are generated: 10 graphs of each class and 10 sets of agent preferences. Then, 100 simulations are performed from different initial allocations for each scenario (couple preference + graph). Two acceptability criteria are considered during the simulations: the individual rationality and the sociability. Four negotiation policies are considered in each case: two allowing only one type of transaction (gifts and swaps) and two allowing several types of transaction ("up to $\langle 1, 1 \rangle$ " and "up to $\langle 2, 2 \rangle$ "). Since gifts cannot be individually rational, some negotiation policies do not exist in societies of individually rational agents.
- 4.8 The resources are initially distributed randomly. The preferences are also generated randomly in the range $\{1..m\}$. For experiments focusing on connectivity, only Erdős-Rényi graphs are used and the probability p for a link to exist between two agents varies from 0.05 to 1. During a negotiation process, the initiator agent is randomly chosen and the speech turn is uniformly distributed: no agent can talk twice before all the others talked at least once. When no one is able to find an acceptable transaction, the negotiation process ends.
- 4.9 The size of the scenarios (50 agents and 250 resources) used for the simulations may seem light in contrast with the claimed scalability of our approach. Yet, only a few studies in the literature include experiments, most of them being purely theoretical. Among the experimental studies, the number of agents is often restricted to less than 10, with a maximum of 20 resources (Estivie *et al.*, 2006; Ramezani & Endriss, 2009; Chevalyere *et al.*, 2007; Andersson & Sandholm, 1998), which is far beyond our parameters. Also, we choose to evaluate the social efficiency. In this purpose, the optimal social value, which is estimated owing to centralized techniques, is used as a reference for comparisons. The complexity of allocation problems is exponential with respect to the population size and to the size of the resources set. Besides, the estimation of the optimal value according to these centralized techniques is very time-consuming. For this reason, the comparison with the estimation of the optimal results is the main limiting factor to the size of our experiments.



Utilitarian negotiations

Impact of the transaction cardinality

- 5.1 Figure 3 shows the impact of the transaction cardinality on negotiation processes within utilitarian societies. It represents the evolution of the utilitarian welfare value in function of the computation time. The efficiency of different negotiation policies, classified with respect to the maximum number of resources proposed by the agents, can also be compared. The best negotiation policy leads to the largest social welfare value in a minimum time.

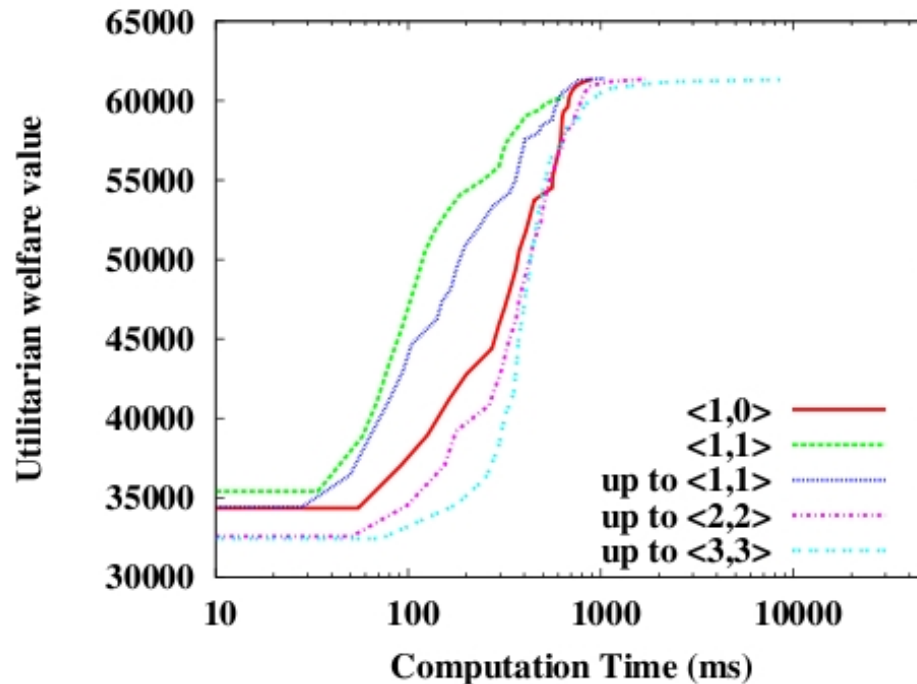


Figure 3: Impact of the transaction cardinality on utilitarian negotiations

Figure 3 shows that, independently of the cardinality of the allowed transactions, all negotiation processes converge towards very close utilitarian welfare values whereas the computation time required for the convergence quite varies. The negotiation policy based on gifts ($\langle 1, 0 \rangle$ transactions) leads to a faster convergence towards the largest welfare value. Larger bilateral transactions do not allow the achievement of higher utilitarian allocations although they are more time consuming. Negotiation processes based either on gifts ($\langle 0, 1 \rangle$ transactions), swaps ($\langle 1, 1 \rangle$ transactions) or both end after about 1 second while 10 seconds are required in the case of the negotiation policy "up to $\langle 3, 3 \rangle$ " for instance. Negotiation processes based on swaps end on socially weaker allocations. Since the initial resource distribution cannot be modified, negotiation processes based on swaps end on weaker local optima. The improvement of the welfare value is quicker when agents negotiate either using "up to $\langle 1, 1 \rangle$ " or $\langle 1, 1 \rangle$ transactions. It can represent an interesting alternative if a good approximation is required in a short time. However, it strongly depends on the mean number of resource per agent. In these experiments, agents own an average of 5 resources in their bundle but larger resource bundles affect the convergence speed. Indeed, larger resource bundles mean a higher number of possible transactions between each pair of agents, and thus lead to a decrease in gradient of the corresponding curves.

Proposition 5 (Utilitarian bilateral transaction decomposition) *Any bilateral transaction satisfying the utilitarian criterion can be decomposed into a sequence of utilitarian gifts leading at least to a socially equivalent allocation.*

Proof. Let us consider a bilateral transaction between two agents $i, j \in \mathcal{P}$ changing the initial allocation A into A' . It can be formulated by definition as follows:

$$\delta_i^j \langle X, 0 \rangle = (\rho_i, \emptyset) \text{ is social} \Rightarrow sw_u(A) < sw_u(A').$$

Two cases can occur.

- All the resources offered by the initiator are more valued by the partner.

$$\forall r \in \rho_i, u_i(r) < u_j(r) \Rightarrow \forall r \in \rho_i, \delta_i^j \langle 1, 0 \rangle = (r, \emptyset) \text{ is social.}$$

In such a case, the decomposition of the initial transaction $\delta_i^j \langle X, 0 \rangle = (\rho_i, \emptyset)$ into a sequence of social $\langle 1, 0 \rangle$ -transactions leading to the same allocation is trivial.

- The initiator values (at least) one resource from its offer more than the partner involved. In such a case, the transaction cannot be split into a sequence of utilitarian gifts. However, this transaction is suboptimal. There exists a transaction of

lesser cardinality leading to a socially more interesting allocation A'' .

$$\exists r \in \rho_i, u_i(r) < u_j(r) \Rightarrow \delta_i \langle X-1, 0 \rangle = (\rho_i \setminus \{r\}, \emptyset) \text{ is social.}$$

$$\text{and } sw_u(A'') > sw_u(A) > sw_u(A).$$

Indeed, removing from the initiator's offer all the resources less valued by the partner constitutes a new transaction leading to a socially greater allocation A'' .

$$\begin{aligned} sw_u(A'') &= sw_u(A) - \sum_{r' \in \rho_i \setminus \{r\}} u_i(r') + \sum_{r' \in \rho_j \setminus \{r\}} u_j(r') \\ &= sw_u(A) + u_i(r) - u_j(r) \\ &> sw_u(A) \end{aligned}$$

This removing condition can be applied as long as offered resources, less valued by the partner, appear in the initiator's offer. The new transaction satisfies the first condition and can be split in a sequence of social gifts. A similar argument can be used with $\langle X, Y \rangle$ -transactions, which can first be decomposed into a $\langle X, 0 \rangle$ -transaction and a $\langle Y, 0 \rangle$ -transaction. Hence, all bilateral transactions satisfying the utilitarian criterion can be decomposed in a sequence of utilitarian gifts either leading to the same allocation (as many gifts as resources in the initiator's offer), or leading to a socially greater allocation (the sequence is shorter than the size of the initiator's offer). \square

- 5.2 Since the utilitarian welfare value achieved is similar regardless of the transaction cardinality, the use of large bilateral transactions is not justified due to important additional costs. Besides, restrictions on the transaction cardinality do not harm the efficiency of negotiation processes.

Utilitarian efficiency

- 5.3 In order to determine the social efficiency of negotiation processes, the optimal social value must be computed according to a centralized technique. In the context of this study, the optimal utilitarian welfare value can be determined using Algorithm 2.

Algorithm 2: Determination of the optimal utilitarian welfare value

Input: Agent population \mathcal{P} , Resource set \mathcal{R}

Output: sw_u^{opt} the optimal utilitarian value

forall $r \in \mathcal{R}$ **do**

$i \leftarrow \underset{k \in \mathcal{P}}{\text{arg max}} u_k(r)$; // search which agent estimates r the most

Add r to $A(i)$; // adds r to agent i 's bundle

end

return $sw_u(A)$;

- 5.4 Table 4 presents the efficiency of negotiation processes based on different negotiation policies, acceptability criteria and classes of contact graph. This table shows the proportion of the optimal welfare value that can be achieved (the greater the proportion, the more efficient the negotiation process).

Table 4: Utilitarian efficiency (%) according to the class of graphs

Graph	Negotiation policy					
	Rational		Social			
	$\langle 1, 1 \rangle$	up to $\langle 2, 2 \rangle$	$\langle 1, 0 \rangle$	$\langle 1, 1 \rangle$	up to $\langle 1, 1 \rangle$	up to $\langle 2, 2 \rangle$
Full	96.6	97.0	100	98.3	100	100
Grid	79.0	81.3	86.2	85.3	86.1	86.1

Erdős-Rényi	94.8	95.0	98.9	97.1	98.9	98.9
Small world	80.8	84.8	91.4	90.0	90.2	90.3

5.5 When considering complete graphs, different negotiation policies always lead to optimal resource allocations. The transactions of weakest cardinality, which achieve optimal allocations, are social $\langle 1, 0 \rangle$ transactions (social gifts). Any negotiation policy that includes social gifts, like "up to $\langle 1, 1 \rangle$ ", "up to $\langle 2, 2 \rangle$ " or "up to $\langle 3, 3 \rangle$ " also achieves socially optimal resource allocations. However, their use leads to important additional costs. *The use of social gifts is sufficient to achieve optimal allocations when the utilitarian welfare is considered.* Table 4 also shows that, independently of the social graph class, rational negotiation processes always lead to socially weaker allocations than social negotiation processes. The restrictive character of the acceptability criterion affects the resource circulation and consequently the quality of the provided solution. We can observe that agents in an artificial society must be able to give resources without counterpart. Negotiation policies that exclude such actions, i.e. if gifts are forbidden or never considered as acceptable, lead to socially weaker results. Generosity between the agents of the population is an essential characteristic to achieve an optimal allocation in utilitarian societies.

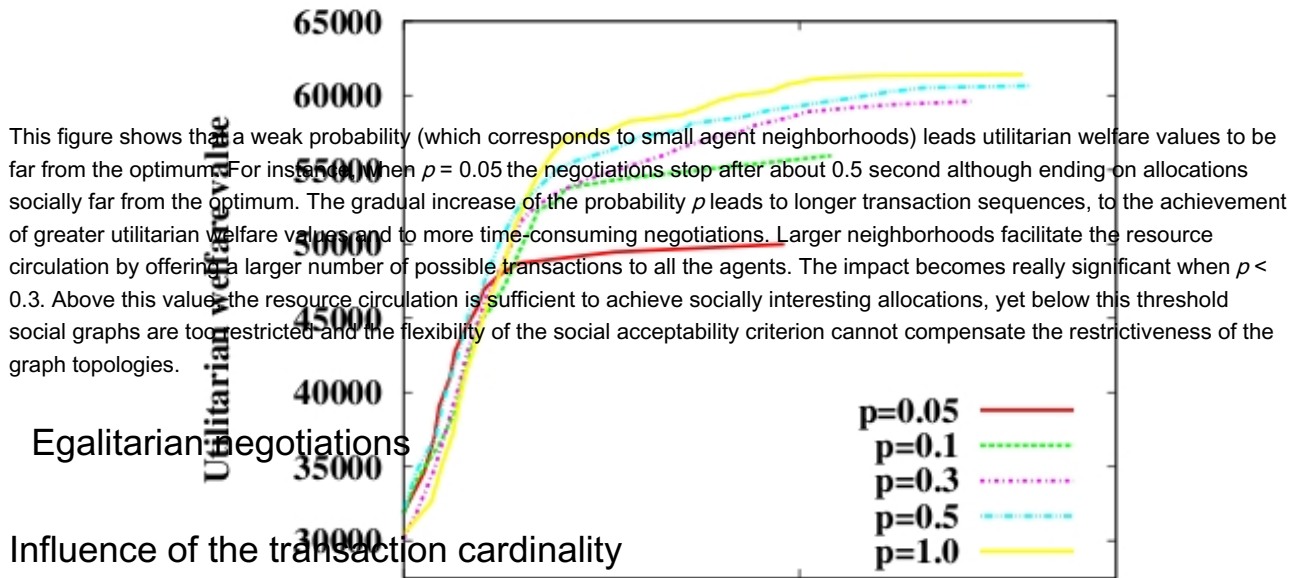
Theorem 6 *Within an utilitarian society where agents express their preferences by means of additive utility functions, negotiation processes based on complete social graphs always converge towards a global optimum using only social $\langle 1, 0 \rangle$ transactions.*

Proof. Since the contact graph is fully connected, any agent $i \in \mathcal{P}$ can communicate with every other agent $j \in \mathcal{P} \setminus \{i\}$. If a social $\langle 1, 0 \rangle$ transaction containing r can be performed between agents i and j , then $u_j(r) > u_i(r)$ according to the definition of a social transaction. It is always possible to create a sequence of social $\langle 1, 0 \rangle$ transactions moving a resource into the bundle of an agent that associates the largest utility value with it. Applying this process to each resource, the resulting allocation is always a global optimum. \square

5.6 The more restrictions on a contact graph, the less efficient the negotiations. The combination of a restricted graph like a grid and the use of rational swaps, which significantly restrict the transaction possibilities (since initial resource distributions cannot be modified), leads to the worst social efficiency: Only 79% of the optimal welfare value can be achieved. When grids are considered, social negotiation processes achieve up to 86.2% of the optimum. The weak mean connectivity handicaps the resource traffic and hence the achievement of socially efficient allocations. Negotiation processes lead to allocations associated with up to 98.9% of the optimal welfare value when Erdős-Rényi graphs ($p = 0.5$) are considered. Only 91.4% of the optimum is achieved when small-worlds are considered. In an Erdős-Rényi graph, the probability for an edge to link any pair of nodes is always the same, while in small-worlds, the probability to link one agent is proportional to the number of agents in its neighborhood. Many agents only have one neighbor and the resource traffic is unequally distributed. Therefore, bottlenecks (i.e. agents that block the resource circulation) may appear. Swaps are the least efficient transactions, but the difference is generally small. Since the number of resources per agent cannot vary, the resource circulation is very limited.

Influence of the social graph connectivity

5.7 The topology of the contact graph affects the resource traffic as well as the negotiation efficiency. Large agent neighborhoods correspond to dense contact graphs which facilitate the circulation of the resources. Figure 4 shows the impact of the mean connectivity on the negotiation processes efficiency. It represents the evolution of the utilitarian welfare value in function of the computation time. Only social gifts are allowed between agents.



Egalitarian negotiations

Influence of the transaction cardinality

6.1 Figure 5 shows the influence of the transaction cardinality on the evolution of egalitarian welfare value during the negotiation processes.

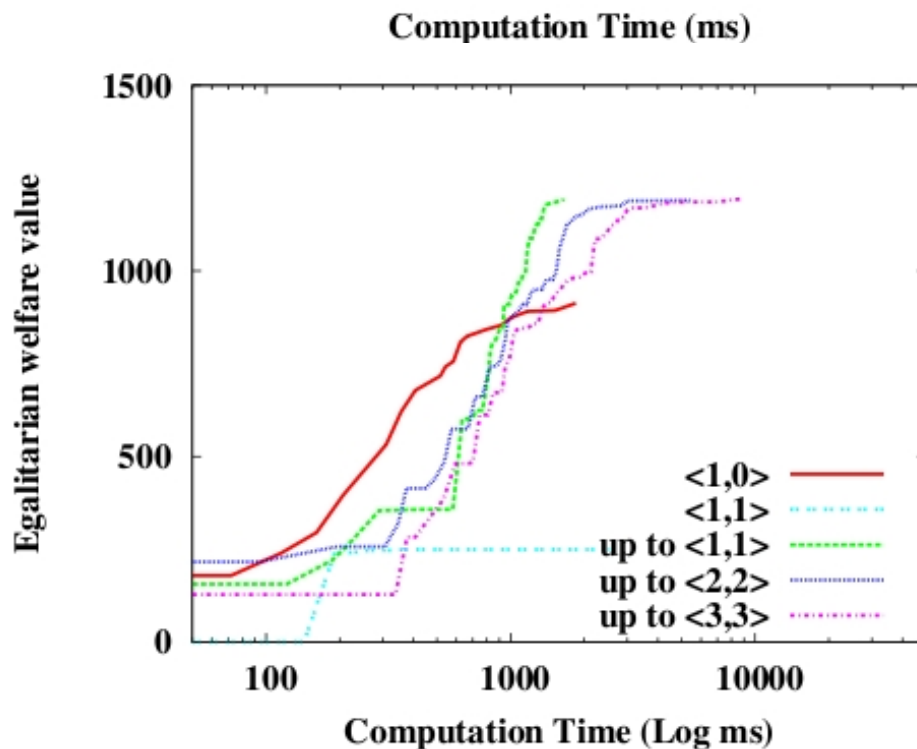


Figure 5: Impact of the transaction cardinality on fair negotiations

6.2 Figure 5 shows first that egalitarian negotiations are much more time-consuming compared to utilitarian negotiations. It also shows that three negotiation policies lead to similar welfare value but different convergence times, while two other negotiation policies achieve weaker results. Indeed, the negotiation policies "up to $\langle 1, 1 \rangle$ ", "up to $\langle 2, 2 \rangle$ " and "up to $\langle 3, 3 \rangle$ " achieve similar social values but are respectively more and more time consuming. The negotiation policy "up to $\langle 1, 1 \rangle$ ", which is included in the two others, is the simplest policy associated with the best efficiency. The other negotiation policies lead to useless additional costs that do not improve the fairness of the artificial society. Several floors can be observed in the evolution of the egalitarian welfare value. These floors characterize specific negotiation periods during which the poorest agent of the population is not involved in the performed transactions, as described previously in Section 3.4.2. Negotiation processes based on social gifts end quickly. However, provided solutions are associated to social values far from the values achieved by larger bilateral transactions. Negotiation processes based on social $\langle 1, 1 \rangle$ transactions (social swaps) require a large number of performed transactions, which barely improves the social welfare value and ends on socially very weak allocations. Since such processes are time consuming and inefficient, the exclusive use of swaps should be avoided. Using a set of allowed transactions larger than $\Delta = \{\langle 1, 0 \rangle, \langle 1, 1 \rangle\}$ is

pointless since it leads to additional costs without any significant improvement on the solution quality. The set of allowed transactions must be larger when fair artificial societies are considered than in the case of utilitarian population.

Egalitarian efficiency

6.3 In order to determine the social efficiency of negotiation processes, the optimal egalitarian value must be computed relying on a centralized technique. However, there does not exist a simple algorithm like in the case of utilitarian societies. Egalitarian resource allocation problems can be formulated by means of a mathematical model and solved using a linear program solver for instance. Our model is based on Boolean variables describing the ownership of a resource by an agent: $x_{ir} = 1$ if resource r belongs to agent i , $x_{ir} = 0$ otherwise. Egalitarian resource allocation problems can thus be written as follows:

$$sw_e^{opt} = \begin{cases} \max \min_{i \in \mathcal{P}} \sum_{r \in \mathcal{R}} u_i(r) x_{ir} \\ \text{s.t.: } \sum_{i \in \mathcal{P}} x_{ir} = 1 & r \in \mathcal{R} \\ x_{ir} \in \{0, 1\} & r \in \mathcal{R}, i \in \mathcal{P}. \end{cases}$$

The objective is the maximization of the poorest agent welfare. Two consistency constraints are also defined. The first ensures that each resource is allocated to a single agent while the second specifies that all resources are atomic, unique and not shareable. Such a technique can estimate the optimal egalitarian value but is very time-consuming.

6.4 Table 5 shows the impact of the graph topology on the egalitarian negotiation efficiency.

Table 5: Egalitarian negotiation efficiency (%) according to the class of graphs

Graph	Negotiation policy					
	Rational		Social			
	(1, 1)	up to (2, 2)	(1, 0)	(1, 1)	up to (1, 1)	up to (2, 2)
Full	19.3	20.8	78.5	24.1	99.9	99.9
Grid	13.9	14.6	66.2	23.6	80.2	80.6
Erdős-Rényi	17.4	20.2	77.3	23.8	96.1	96.6
Small world	13.1	13.9	63.8	23.4	78.1	78.2

Table 5 shows that generally, negotiations among rational agents achieve unfair allocations. Indeed, independently of the kinds of allowed transactions and of the social graph topology, rational negotiation processes end far from the optimal welfare value. Only 20% of the optimal welfare value is achieved in the best cases. The individual rationality, which is widely used in the literature, is not an efficient acceptability criterion. Even on complete graphs, no social negotiation policy can guarantee the achievement of egalitarian optima. Whereas social gifts are well adapted to the solution of utilitarian problems, they do not suit the negotiations within egalitarian societies. Only 78.5% of the optimum can be achieved in the best cases. Indeed, after a finite number of transactions, agents can not give a resource without becoming poorer than their partners were initially. The exclusive use of gifts is then not sufficient to lead negotiations to socially efficient resource allocations. Negotiations based only on social swaps lead to severely sub-optimal resource allocations with an efficiency of 24.1% on complete social graphs in the best case. Such a weak efficiency is mainly due to the inherent constraints of swap transactions. Since the resource distribution cannot be modified, a poor agent who only has few resources initially penalizes a lot the egalitarian negotiation process. When both gifts and swaps are allowed, the negotiation efficiency is really close to the optimum. Larger bilateral transactions bring a small improvement on the fairness among agents but are much more expensive to determine.

Theorem 7 Within an egalitarian society where agents express their preferences by means of additive utility functions, bilateral transactions cannot guarantee the achievement of an egalitarian optimum, independently of the social graph considered.

Proof. Let us consider a counter-example, based on a population of three agents $\mathcal{P} = \{1, 2, 3\}$ and a set of three available resources $\mathcal{R} = \{r_1, r_2, r_3\}$. The agent preferences are described in Table 6.

Table 6: Insufficiency of bilateral transactions in egalitarian negotiations – Agent preferences

$u_i(r_j)$		Resource Set \mathcal{R}		
		r_1	r_2	r_3
Population \mathcal{P}	1	2	1	5
	2	5	2	1
	3	1	5	2

The complete social graph is described in Figure 6 with the initial resource allocation $A = \{r_1\}\{r_2\}\{r_3\}$.

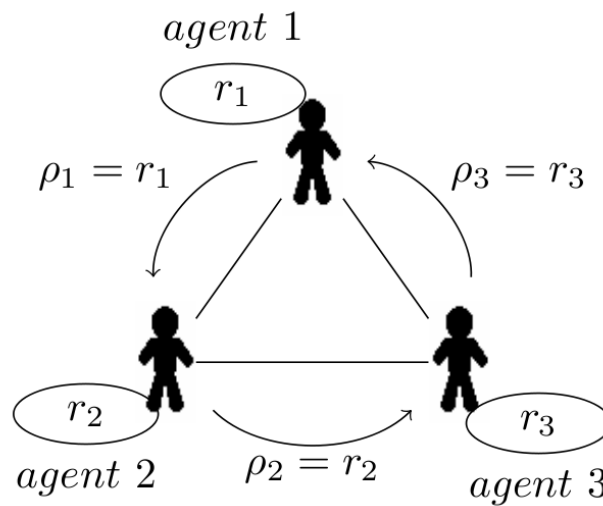


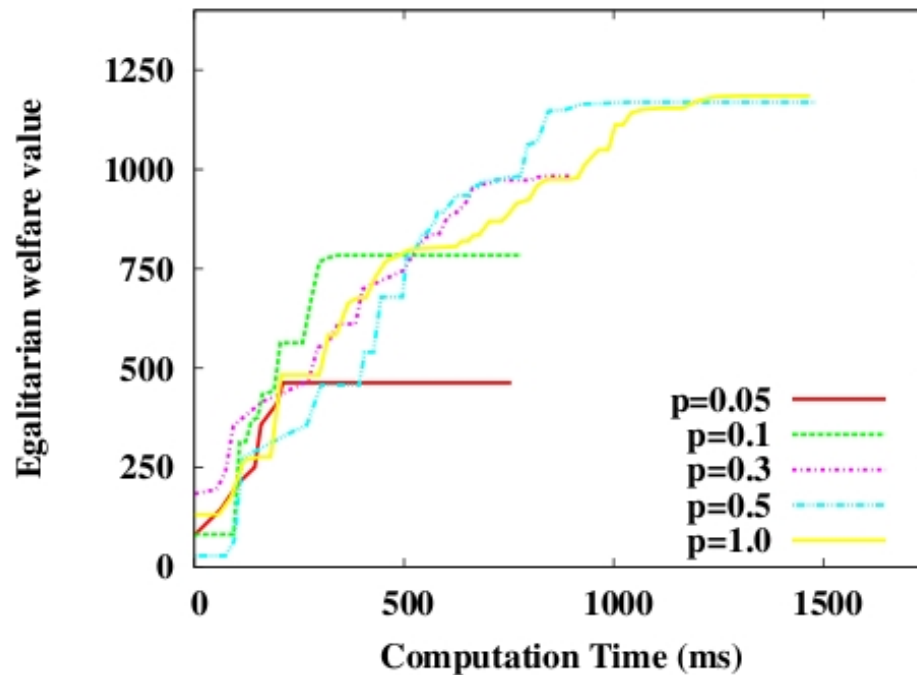
Figure 6: Deadlock in egalitarian negotiations

This figure also describes the only egalitarian transaction that would be acceptable. No sequence of acceptable bilateral transactions can lead to an optimal resource allocation. Six gifts are possible but none can be performed since they are not social. Indeed, if an agent gives a resource, its bundle becomes empty and the egalitarian welfare value becomes null. Three swaps are possible, but for each the welfare value decreases, which means that the transaction is not acceptable. Hence, even if the multiagent system is completely connected, the optimal solution cannot be achieved using only bilateral transactions. Only a multilateral transaction corresponding to three simultaneous gifts is acceptable as described in Figure 6. Since bilateral transactions are not sufficient when negotiations are based on a complete social graph, they are also not sufficient when the social graph is restricted. In such cases, less transactions are possible and unacceptable transactions on a complete social graph are still unacceptable on a restricted social graph.

6.6 Graphs of weaker mean connectivity like grids lead negotiation processes to socially weaker allocations. In the case of small worlds, many agents only have a few neighbors, which may penalize egalitarian negotiations. Indeed, if such agents cannot identify an acceptable transaction with their unique neighbor, some resources may be trapped in their bundle.

Impact of the contact graph connectivity

6.7 Figure 7 presents the impact of the mean connectivity on negotiations within egalitarian societies.



Similarly to utilitarian negotiations, this figure shows that a high probability (corresponding to a dense social graph) leads to longer sequences of transactions during negotiation processes, moreover achieving a higher welfare value. Larger neighborhoods facilitate the resource circulation by offering larger numbers of possible transactions to all agents. The impact of the connectivity is important provided the probability p of generating edges is very low. Like in negotiations on utilitarian societies, the impact of the connectivity is not linear: it becomes really significant below $p \leq 0.5$. Societies require a denser contact graph to achieve interesting allocations when fairness is considered.

Conclusion

- 7.1 A large variety of applications can be modeled as resource reallocation problems. Yet, studies investigating such problems do not always consider an adequately realistic context. Considering that neither omniscient agents nor unrestricted interaction possibilities represent a realistic environment, the knowledge of the agents in our approach is limited to local information and their possible interaction is defined by a contact graph. Compensatory payments are also prohibited in order to avoid infinite agent wallet.
- 7.2 We also consider that centralized techniques are not best suited for searching transaction sequences leading to an optimal allocation. Therefore, we focus in this paper on distributing solving methods based on agent negotiations. We seek to define the optimal behavior maximizing the welfare of the whole society. To that end, we propose the agent behavior and the negotiation policy allowing the achievement of socially optimal allocations according to different welfare functions. The finiteness of the negotiation processes is guaranteed by an acceptability criterion enabling the agents to determine the profitability of a transaction on a local basis. In this paper, we show that negotiations between individually rational agents do not lead to socially interesting allocations. We propose a new criterion, sociability, that certifies that agents accept any transaction that do not harm the society. The expression of this social acceptability criterion is detailed according to the four main welfare notions. The agent behavior required to achieve socially interesting state in agent societies is also described.
- 7.3 We choose to evaluate different aspects of negotiation processes in a large number of simulations. The efficiency of the negotiation settings is quantified by means of a comparison with optimal solutions estimated by centralized techniques. We also evaluate the impact of the transaction cardinality, of the graph connectivity and the quality of provided solutions. We show that the use of large bilateral transactions is not essential to achieve optimal allocations. Indeed, it does not lead to significant improvements of the solution but to an important increase of the computational costs. Bilateral transactions of restricted cardinality are sufficient to achieve socially interesting allocations.
- 7.4 The most efficient negotiation policies are summarized in Table 7 according to the social welfare notion considered.

Utilitarian

A negotiation policy based on social gifts is sufficient to achieve optimal allocations when complete contact graphs are

Egalitarian

considered. This negotiation policy also leads to the best results on restricted graphs (structured and random graphs). The use of bilateral transactions cannot guarantee the achievement of optimal allocations, even on complete contact graphs. However, a negotiation policy based on social gifts and social swaps is sufficient to achieve socially efficient allocations.

Table 7: Summary of efficient negotiation policies according to different scenarios

Contact graph Class	Welfare notions	
	Utilitarian	Egalitarian
Complete	optimal social $\langle 1, 0 \rangle$ transactions	suboptimal (99%) social $\langle 1, 0 \rangle$ transactions
Restricted	suboptimal social "up to $\langle 1, 1 \rangle$ " transactions	suboptimal social "up to $\langle 1, 1 \rangle$ " transactions

7.5 Unsurprisingly, we find that the topology of the contact graphs has a significant impact on the efficiency of the negotiation processes, yet lessened when utilitarian societies are considered. A very weak mean connectivity will drastically affect the efficiency whereas an irregular topology will not. In fair artificial societies, a more important connectivity is required to achieve fair allocations. Regular topologies also lead to better results because isolated agents trap resources easily, affecting the efficiency of the negotiations.



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