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Multiagent Resource Allocation and Welfare Engineering

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The allocation of indivisible resources amongst autonomous agents is a central research issue in the multiagent systems community. To date, most work in this area has concentrated on *combinatorial auctions* [2]. In this case, the allocation mechanism is *centralised*. Agents report their preferences by submitting bids for different bundles of resources and the auctioneer is then faced with the so-called winner determination problem, namely the problem of finding an allocation that maximises a suitable metric (usually the auctioneer's revenue). On the other hand, in truly *distributed* approaches to multiagent resource allocation, allocations emerge as a consequence of individual agents locally agreeing on a sequence of deals to exchange some of the items they currently have in their possession.

Welfare Engineering

Multiagent systems are often interpreted as *societies of agents* and we can employ formal tools from welfare economics and social choice theory to analyse their properties [1]. While, at the local level, agents arrange deals in accordance with their individual preferences, at the global level (say, from a system designer's point of view) we are interested in negotiation processes that lead to allocations of resources that are *socially optimal*. Different options for how to interpret the concept of a socially optimal allocation are discussed in "Notions of Social Welfare" on the next page. While most work in multiagent systems to date has focussed on the Pareto condition and the (utilitarian) interpretation of social welfare as sum-of-utilities, we believe that the full range of notions of social welfare investigated in the social sciences can be of interest to the multiagent systems community.

In recent work, we have therefore put forward the idea of *welfare engineering* [5]. In classical welfare economics, the question as to what notion of social welfare is the right one is mostly discussed from a philosophical or ethical point of view. Different answers to this question will typically claim to be rather general in scope and are, of course, understood to apply to human society. In contrast to this, welfare engineering is concerned with choosing, and possibly designing, tailor-made social welfare orderings that are appropriate for *specific* applications; and the focus is on societies of *artificial* agents. An example is elitist social welfare ordering, which favours states in which the most successful agent enjoys a very high utility. This would be considered inappropriate for human society, but it may be just the right performance indicator for a distributed computing application where several agents are working towards their goals, but the system designer is only interested in at least one of them achieving their objective as quickly as possible.

A second aspect of welfare engineering is concerned with the design of appropriate rationality criteria and social interaction mechanisms for negotiating agents in view of different notions of social welfare. By "appropriate" we mean criteria and mechanisms that ensure the convergence of the negotiation process to an allocation that is optimal with respect to the chosen social criterion. This aspect of welfare engineering may be dubbed "*inverse* welfare economics" (in analogy to mechanism design, which is sometimes referred to as inverse game theory). Examples for rationality criteria include "accept any deal that strictly increases your utility" or "accept any deal that reduces inequality".

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Multilateral Negotiation

An important aspect of the negotiation framework we have considered in our work is that agents use relatively simple rationality criteria to decide whether or not to accept a proposed deal, but interaction patterns may be complex. In particular, truly multilateral deals, that is, deals involving more than two agents at a time, are possible [6]. For instance, an agent may only be prepared to buy a flight ticket from another agent if it can obtain two opera tickets from a third agent *at the same time*.

While it is usually possible to design reasonable rationality criteria that can be applied locally and that guarantee the desired convergence property, such results often depend on the assumption that agents are able to negotiate any multilateral deal, however complex in structure. Given that implementing such a negotiation protocol may prove difficult in practice, it is also important to investigate under what circumstances a simpler interaction mechanism may suffice. In some cases, it is also possible to guarantee convergence to a socially optimal allocation when agents only negotiate very simple types of deals. For instance, deals involving only a single resource (and thereby only two agents) at a time are sufficient to negotiate allocations with maximal utilitarian social welfare amongst strictly selfish agents, provided all agents use modular utility functions, and compensatory side payments are possible.

Aspects of Complexity

Another important direction of research concerns the complexity of multiagent resource allocation. Firstly, we may ask for the computational complexity of finding a socially optimal allocation. The winner determination problem in combinatorial auctions is known to be NP-hard and the same applies to the problem of finding an allocation that maximises the sum of utilities of all agents (utilitarian social welfare). Another question that has been investigated concerns the complexity of deciding whether it is possible to reach a socially optimal allocation by means of a sequence of bilateral deals involving only one resource each for a given scenario. This problem has also been shown to be NP-hard [3]. Both of these problems are *abstract* in the sense that they are not problems that would be faced directly by agents when engaged in negotiation.

Notions of Social Welfare

The literature on welfare economics and social choice theory offers a wide range of different notions of social welfare that promise to have interesting applications in multiagent systems.

- The **utilitarian** social welfare is defined as the sum of individual utilities. This provides a measure of overall (as well as average) profit in e-commerce applications.
- The **egalitarian** social welfare is given by the utility of the poorest agent in a society. This notion offers a level of *fairness* and may be an appropriate measure of performance when we have to satisfy the minimal needs of a large number of customers.
- The **elitist** social welfare, on the contrary, is given by the utility of the richest agent. This can be useful in cooperation-based applications where we require only one agent to achieve its goals.
- The **Nash product** is defined as the product of individual utilities and favours both increases in overall utility and inequality-reducing redistributions.

The above are all *quantitative* measures of social welfare. The following are examples for *qualitative* criteria to identify system states that are optimal from a social point of view.

- A **Pareto optimal** state is a state where it is not possible to increase the utility of some agents without reducing that of any of the others. This provides a minimalistic measure of performance for a wide range of applications.
- The notion of **Lorenz optimality** provides a compromise between the utilitarian and the egalitarian point of view by identifying states where the sum of utilities of the k poorest agents cannot be increased for some and maintained for all other values of k.
- In the context of multiagent resource allocation, an **envy-free** allocation is an allocation where no agent would rather have the bundle allocated to one of the other agents. This provides another notion of fairness, although envy-free allocations do not always exist.

As far as concrete negotiation is concerned, we can distinguish at least four different aspects of complexity [4]. They are epitomised by the following questions:

- How many deals are required to reach an optimal allocation?
- How many communicative exchanges are required to agree on one such deal?
- How expressive a communication language do we require?
- How complex is the reasoning task faced by each agent at each step?

The first type of complexity takes individual deals as primitives, abstracting from their inherent complexity, and evaluates the length of a negotiation process as a whole. At the next lower level, we have to consider the complexity of negotiating a single deal in such a sequence of deals converging to a socially optimal allocation. Here complexity is measured in terms of the number of messages sent back and forth between the agents before a deal can be agreed upon. Finally, we have to consider the complexity of deciding what message to send at a given stage; this is the fourth type. The third type is somewhat orthogonal to the other points as it concerns the complexity of a language: how rich a communication language do we require, say, to be able to specify proposals and counterproposals for multilateral deals over bundles of resources?

Communication Complexity

The first three of the above questions all relate to the *communication complexity* of negotiation. This term is borrowed from the literature on distributed computing, where it is used to refer to the number of bits that the nodes in a distributed system need to exchange to be able to jointly compute the value of a given function. In the context of negotiation, this means that we focus on the length of negotiation processes and the amount of information that agents exchange, rather than on purely computational aspects. We believe that this provides an interesting and important perspective on negotiation in multiagent systems that has not yet received the full attention it deserves.

We hope to have demonstrated that multiagent resource allocation is an interesting and worthwhile area of research. What makes it particularly attractive is its interdisciplinary character: it brings together ideas from the socio-economic sciences on the one hand, and from computing and AI on the other. We have mentioned some recent results here, but a host of research challenges and open problems still remain. We conclude by listing a selection of these:

- *Conceptual issues*: The idea of using different and novel notions of social welfare raises the question of the "ethics" of multiagent systems.
- *Methodological issues*: The basic idea of welfare engineering is still a far way from a fully-fledged design methodology.
- *Protocol design*: Our work demonstrates the need to design protocols for multilateral negotiation.
- *Technical issues*: There are still many open problems regarding complexity and convergence properties.
- *Algorithm design*: Is it possible to exploit known optimisation algorithms to guide negotiation?
- *Experimentation*: Building simulators for distributed resource allocation may prove useful in developing powerful negotiation heuristics.

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