J Supercomput (2007) 42: 181–199
DOI 10.1007/s11227-007-0131-7

Grid resource management based on economic mechanisms

Chuliang Weng · Minglu Li · Xinda Lu

Published online: 4 May 2007

Abstract Resources in the grid context belong to different control organizations with different interest, therefore the economic interest of each grid participant should be considered. The economic mechanism can guarantee the interest of participants in the grid with fairness and efficiency. In this paper, an economic-based resource management framework is put forward for grid computing, and then how to determine the price of resources with the economic mechanism is studied. A general equilibrium method is presented for general resources and a double auction method is proposed for special resources in the grid environment, respectively. Simulations are performed and experimental results indicate that the two methods are effective for corresponding application scenarios.

Keywords Grid computing · Resource management · Economic mechanism · Resource pricing · Double auction

1 Introduction

The goal of grid computing is to achieve all kinds of resources sharing within and between organizations. Grid resources are geographically distributed across multiple organizations, which have their own interest on these resources. However, currently grid resources are usually assumed to be provided by the individual organizations without considering the necessary interest of these grid participants. In other words, a grid community was considered as a *utopia*, where grid participants are expected that are willing to provide all kinds of computational resources selflessly.

Expanded version of a paper presented at CCGrid 2005.

C. Weng (✉) · M. Li · X. Lu
Department of Computer Science and Engineering, Shanghai Jiao Tong University,
Shanghai 200240, China
e-mail: weng-cl@cs.sjtu.edu.cn

Currently, grid technology is establishing the way out of the academic incubator and into industry environments. Suitable kinds of business models or economic mechanisms should be considered in order to guarantee the interest of grid participants, and achieve the fairness and the efficiency of resource sharing between different individuals. So we believe that in the long run the economic factor should be introduced into the issue of resource allocation in the grid context.

In this paper, our main contributions are as follows. We propose an economic-based resource management framework for grid computing, where resources are organized hierarchically, and the economic elements are conjoined with each resource level independently. According to its characteristic, resource in the grid environment can be classified into two kinds, one kind is the general resource in the grid, and the other kind is the special resource. Then we present a group pricing algorithm based on the general equilibrium analysis for general resources in the grid context, and bring forward a double auction mechanism for special resources with the transaction fee adjusted flexibly, which are different from the existing works.

This paper is organized as follows. In Sect. 2, a brief overview is given for the current research on applying economic mechanisms to grid computing and other distributed computing. A framework of resource management is described in Sect. 3. A group pricing algorithm is presented with experiments for general resources in the grid context in Sect. 4. In Sect. 5, a double auction method is proposed with experiments for special resources in the grid context. Finally, we conclude this paper in Sect. 6.

2 Related works

At present, researches on resource management for grid computing based on the general equilibrium theory include works [1–4]: the centralized pricing method is studied in [1, 2], and the distributed pricing method is studied in [3]. In GRACE [4, 5], a significant research is performed on applying economic mechanisms to resource management for grid computing, however, resource prices were given to them artificially in economic-based resource scheduling experiments, leaving no space for optimization of resources allocation [6].

Some other existed methods had been studied in the previous distributed computing and E-commerce, etc. Distributed pricing WALRAS algorithm is presented in [7], and the suitable situation of this algorithm is also discussed. Distributed independent pricing methods and centralized simultaneous pricing methods are compared in [8].

Study on applying auction models to price resources in distributed systems includes [9–13]: the double auction is applied to the e-commerce in [9], and the single Vickery auction is used to manage resources in the network of heterogeneous workstations in [10], and the double auction model and the one-side auction model are applied to allocate resource over the Internet in [11, 12], and the double auction is applied to allocate the electrical power in the computational electricity market [13]. Tycoon [14] is designed and implemented as a market-based distributed resource allocation system based on an auction share scheduling algorithm.

Differing from these existed works, we focus on dealing with resource variety in the grid environment when considering the economic factors, where some general resources are provided and demanded in multiple distributed resource control domains, while some special resources are provided or demanded only in a single resource control domain. Then we try to solve the problem of the resource organization means, and how to determine the price of resources when applying economic mechanisms to the grid environment.

3 The resource management framework

In this section, we focus on the problem of organizing the distributed, autonomous, and dynamic resources in the grid environment.

3.1 Hierarchical organization

The scalability of the resource organization model is vital to the large system, especially for grid computing. Insight into the early grid resource management architecture [15] and the recent economic-based GRACE [4], we can find out that the hierarchical model is very suitable for the grid context.

In the future grid context, there are many resource providers or service providers, which provide from lower-level computational resources to higher-level services. One participant can play different roles in different levels, such as one service provider who assembles multiple lower-level computational resources or even services to provide a new service to others. Therefore from the point of view of lower-level resource providers, this participant is a resource requester instead of a service provider. Correspondingly, it is necessary to consider economic factors at each resource level in the architecture.

3.2 Virtualization

Addition to the hierarchical model, resource virtualization can simplify the hierarchical organization of resources in the grid context. Virtualization can implement the consistent resource access across multiple heterogeneous platforms with local or remote location transparency, and also can let map of multiple logical resource instances onto the same physical resource [16]. Moreover, virtualization can allow the composition of services to form more sophisticated services.

For simplicity, resources in this paper represent not only lower-level computational resources such as CPU, memory, and storage, but also various higher-level services such as an image processing service. Another similar term reflecting this concept is "service".

3.3 Economic mechanism

According to the characteristic of resources in the grid context, resources maybe belong to different individual organizations, that is, resources in the grid is autonomous. These different organizations have themselves' selfishness for resources, so it is impracticable that different organizations are expected to share their resources unselfishly with each other.

However, in the current grid community, grid resources are expected to be provided by grid participants without well considering the necessary interest of these resources' providers. For implementing the grid blueprint [17], the economic mechanism should be considered for resource sharing in the grid context, in order to guarantee the interest of each grid participant. Also this is the precondition of the grid technology coming into the wide application.

Based on the economic mechanism, resource sharing management can be decomposed into two sub-problems. One is how to determine the price of resources in accordance with the dynamic supply and demand, and the other is how to allocate resources for achieving the goal of high efficient utilization of resources in response to current resource prices. In this paper, we focus on the first problem, i.e., how to determine the price of resources, which will be discussed in the following sections. The second problem is dependent on the specific application.

3.4 A resource management framework

Considering the above characteristics of resources in the grid context, we propose a resource management framework as Fig. 1, which is based on hierarchy and virtualization, and considers the economic mechanism.

The more explanation is given for this framework. In the hierarchical architecture, at the bottom are all kinds of physical resources, which at least include CPU, memory, storage, bandwidth, and also may include scientific instruments such as medical instruments or astronomical telescopes, etc. The primary resource level, which could encapsulate these physical resources into virtual resources or WS-Resource in accordance with WS-Resource Framework [18], will deal with resource pricing and accounting. In this paper, we focus on the economic-based resource management issue, and how to implement these mechanisms according to WS-Resource Framework is

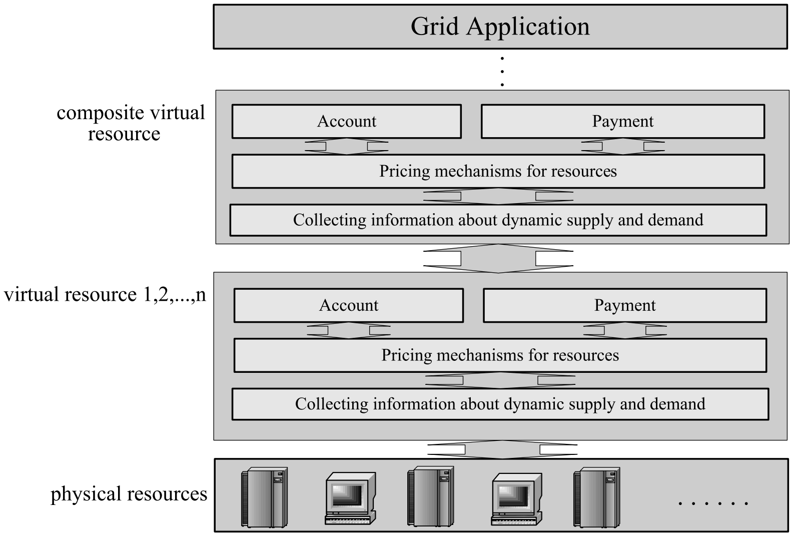


Fig. 1 The framework for resource management

beyond the scope of this paper. On the basis of the virtual resources, composite virtual resources can be built. Correspondingly, the composite virtual resource providers are the customers of the basic virtual resource providers, and are the resource providers for higher-level virtual resources or grid applications.

In this framework, the resource pricing and accounting mechanism are independent on resource levels, that is, the resource pricing mechanism on the higher level has no necessary relation with the lower level. Instead, appropriate mechanisms are chosen according to the characteristic of virtual resources on this level. This property is helpful for implementing the scalability of the pricing mechanism in the grid system.

There are many economic mechanisms in economics [4, 19], which include commodity market (the general equilibrium theory), bargaining model, auction model, etc. In this paper, we adopt the jointed way of commodity market model and auction model for the proposed framework, which is more suitable for distributed systems. The motivation of conjoining the two mechanisms for resource pricing is that commodity market model can be used to determine price for the general resources, and auction model can be used to determine price for the special kind of resources in the grid context, so the jointed methods can deal with the diversity of resources in the grid.

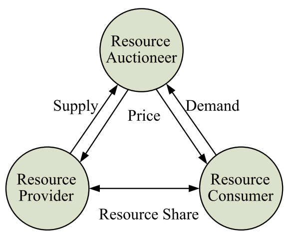
Correspondingly, based on the property of resources in the grid environment, we focus on adapting the two economic mechanisms in order to present a pricing algorithm for commodity market model and put forward a double auction mechanism, respectively.

3.5 Resource roles

Before further describing the algorithms, we will discuss roles of grid participants in the resource management firstly. The grid participants can be classified into three roles, that is, resource providers, resource consumers and resource auctioneers, illustrated as Fig. 2.

It is the resource auctioneer that determines the price of resources and even the resource allocation, based on the supply and demand of resources in the corresponding resource level. In each resource level, the resource provider represents the grid participant who can provide the resource to the outside, and the resource consumer in this level will ask the outside for the resource. In short, the relation illustrated as Fig. 2 exists in each resource level.

Fig. 2 Operation mechanism



4 General equilibrium method for general resources

Usually there are multiple resources in the commodity market, one resource's price has relation to the other resources, and the supply and demand of one resource also has relation to others. Adjusting the price of one kind of resource will result in the change of the other resources' price, so it is the general equilibrium theory [20] that will deal with how to adjust the price of all resources to achieve the equilibrium in the global range instead of in the local range.

Similarly, there are many kinds of resources in the grid context, and how to adjust the price of many general resources is an open issue for the grid community, which expects to be solved with the general equilibrium model.

With the general equilibrium theory, all traders will submit their supply and demand to one auctioneer according to a certain price. And it is the auctioneer that calculates the excess demand and adjusts the price correspondingly. This procedure will be repeated until the excess demand of all resources equals to zero theoretically.

That is, it is the *centralized pricing method* to adjust the price, in which the information of all kinds of resources is sent to a centralized auctioneer, which will calculate the new price vector based on the supply and demand of all resources. Intuitively, it is not suitable for large-scale systems. So the distributed pricing method occurs, i.e. the WALRAS algorithm [7], in which the price of each kind of resource is determined by a dedicated auctioneer asynchronously, however the convergent speed is too slow because of the price correlation between different resources.

In this section, we introduce a new pricing algorithm for the grid context, that is, a group pricing algorithm in the proposed resource management framework.

4.1 The pricing schema

For avoiding the slow convergence speed of pricing in the WALRAS algorithm [7], we proposes a new pricing schema. That is, resources in the system are divided into multiple groups, and each auctioneer is responsible for adjusting the price of one group of resources, instead of one kind of resource, which is presented in WALRAS algorithm [7].

As Fig. 3 illustrated, it is the resource trader that represents a resource control domain to express the supply and demand of resources in this domain, and it is the auctioneer that is responsible for adjusting the price of one group of resources. In this pricing schema, these auctioneers adjust the price of the corresponding groups of resources respectively in the grid context, in order to achieve the equilibrium of the supply and demand of all resources in the long run. Auctioneers and resource traders could communicate by the means of the bottom grid infrastructure, which can be based on the globus toolkit or others.

As the pricing procedure is a repeated procedure, that is, the bidding phase of traders and the adjusting price phase of auctioneers are repeating in turn. In economics, that is a tâtonnement or groping process [20]. In the distributed pricing means, the iterative process will bring the overhead into the pricing schema. Therefore, how to group resources and how to organize traders and auctioneers to partici-

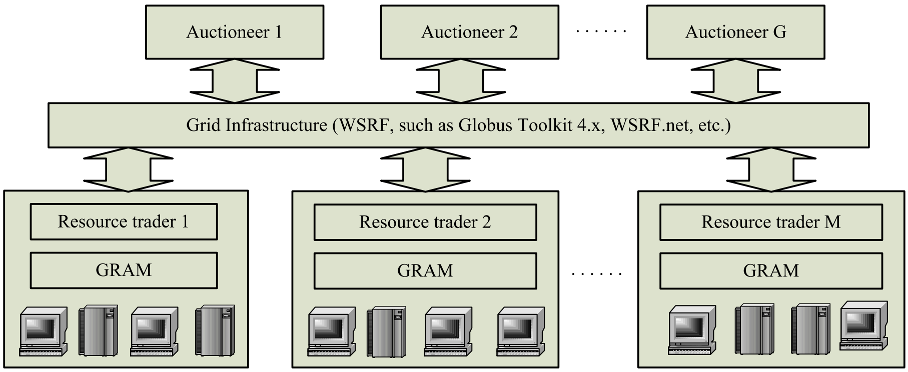


Fig. 3 The pricing schema for general resources

pate in the pricing process are open issues for minimizing the overhead, which will be discussed in the following section.

4.2 The pricing algorithm

In the section, we present a group pricing method in accordance with the above schema, which classifies resources into multiple resource groups according to the degree of price correlation. Usually the price of one kind of resource is dependent on the price of the other kind, then the two kinds of resources have high degree of price correlation. The degree of price correlation reflects how the price of one kind of resource impacts the price of the other. There is weak price correlation between two different resource groups and strong price correlation among one resource group. Among one resource group, the price of resources is adjusted with the centralized method. And the price between different resource groups is adjusted by the independently distributed means.

When the change of the supply and demand of resources invokes a tâtonnement process, the price of one resource group is adjusted independently from the other groups, and the price of resources in the same resource group is adjusted simultaneously according to the equilibrium of the resource group. This procedure is repeated until the global equilibrium of all resources reaches. The group pricing algorithm includes the auctioneer algorithm and the trader algorithm.

The total number of resource traders in the grid system is denoted by M, and N denotes the total number of resource kind. According to the degree of price correlation, resources are divided into G groups, and correspondingly the number of auctioneers also is G. With the G auctioneers, the price of all resources are adjusted gradually. The number of resource kind in resource group k is n_k.

The group pricing algorithm consists of the auctioneer algorithm and the trader algorithm, which are described as Table 1 and Table 2 respectively. For resource group k, the price of the resource group is denoted by $\mathbf{p}_k = (p_{k1}, p_{k2}, \ldots, p_{k,n_k})$, and is adjusted by auctioneer A_k as Table 1.

After auctioneers complete one round of pricing, each resource trader obtains the new price vector $\mathbf{P}^* = (\mathbf{p}_1^*, \mathbf{p}_2^*, \ldots, \mathbf{p}_G^*)$ and the flag vector $\mathbf{F}^p = (f_1^p, f_2^p, \ldots, f_G^p)$,

Table 1 The algorithm for auctioneers

For auctioneer A_k:

(1) Initialize the price vector of resources with the previous equilibrium price, and denoted as $\mathbf{p}_k^0$.
(2) Receive the excess demand function $\mathbf{z}_{ki}(\mathbf{p}_k)$ from resource trader i, $i = 1, 2, \ldots, M$, and

$\mathbf{Z}_k(\mathbf{p}_k) = \sum_{i=1}^{M} \mathbf{z}_{ki}(\mathbf{p}_k)$.

(3) Calculate the new price vector $\mathbf{p}_k^*$.
Solving the following equation by the Newton method with the initial parameter $\mathbf{p}_k^0$.

$\mathbf{Z}_k(\mathbf{p}_k) = \sum_{i=1}^{M} \mathbf{z}_{ki}(\mathbf{p}_k) = 0$.

(4) Determine the amplitude of the price variation.
According to the given price threshold δ, the flag for the price variation is determined as follows, where Am is a vector norms, and $Am = \|\mathbf{p}_k^* - \mathbf{p}_k^0\|_\infty$.
$f_k^p = \begin{cases} 0 & Am < \delta, \\ 1 & Am \geq \delta. \end{cases}$
(5) Send the new price vector $\mathbf{p}_k^*$ and the flag f_k^p for the price variation to all resource traders.

EndFor

Table 2 The algorithm for resource traders

For resource trader i:

for $(j = 1; j <= G; j++)$
(1) Fixup the price vector p_{-j} of resource group $-j$;
(2) Determine the excess demand function $\mathbf{z}_{ji}(\mathbf{p}_j)$ of itself;
(3) Send $\mathbf{z}_{ji}(\mathbf{p}_j)$ to auctioneer $\boldsymbol{A}_j$.

EndFor

by integrating the individual price vector $\mathbf{p}_k^*$ and the individual flag f_k^p received from auctioneer $A_k(k = 1, 2, \ldots, G)$. If $\mathbf{F}^p = \mathbf{0}$, i.e., the new price vector satisfies: $\mathbf{Z}(\mathbf{P}^*) \approx \mathbf{0}$, then $\mathbf{P}^*$ is a new equilibrium price vector. Otherwise, resource traders need to calculate new excess demand functions according to the algorithm for resource traders illustrated as Table 2. After that, the auctioneer will repeat the execution of the algorithm of it.

Summarily, when the supply and demand of resources in the system has a change over a certain threshold, each auctioneer and each trader will repeatedly carry out their algorithms by turns respectively until $\mathbf{F}^p = \mathbf{0}$, which means that a new equilibrium achieves.

4.3 Experiments and results

In the section, we will perform simulation experiments to compare the performance of the group pricing algorithm presented in this paper with the performance of the WALRAS algorithm [7] and the traditional centralized pricing method.

There are many utility functions in economics, and the CES (constant elasticity of substitution) utility function is adopted for validating the WALRAS algorithm [7]. Therefore, we will also choose the CES utility function for valid compares. Then the utility function is as follows, where $X = (x_1, x_2, \ldots, x_n)$ is the consumption bundle.

$$u(\mathbf{x}) = \left(\sum_{i=1}^{N} \alpha_i^{1/\sigma} x_i^{(\sigma-1)/\sigma} \right)^{\sigma/(\sigma-1)}. \quad (1)$$

We choose the performance metrics:

(1) the number of iteration of auctioneers and traders executing their algorithms by turns for achieving a new equilibrium;
(2) the square root of sum of the square of excess demand for all resources, which reflects the global convergence degree during the pricing process.

We set $\sigma = 2$, and randomly generate the α_i coefficient from a uniform distribution [0.1, 200]. The number of resource domains is 30, and endowments for resource traders are randomly generated from a uniform distribution [2000, 3000], and the total volume of each resource is randomly generated from a uniform distribution [540, 1500].

(1) The first situation is that the number of resource kind is 10. For the group pricing algorithm, resources are divided into 2 resource groups according to the degree of price correlation, correspondingly, there are two auctioneers in the group pricing algorithm. Meanwhile, each auctioneer is responsible for one kind of resources in the WALRAS algorithm, and there is only one central auctioneer in the traditional centralized pricing method. The experimental result is shown as Fig. 4(a) and Table 3.
(2) The second situation is that the number of resource kind is 20. For the group pricing algorithm, resources are divided into 3 resource groups according to the degree of price correlation, correspondingly, there are three auctioneers in the group pricing algorithm. The WALRAS algorithm and the centralized pricing method are similar as the above situation. The experimental result is shown as Fig. 4(b) and Table 3.

Although, the performance of the traditional centralized pricing method is the best in the experiments, however, it is based on the centralized means for gathering resource information synchronously, which is impossible in the grid environment. So it

Table 3 The cycles of adjusting price for achieving equilibrium

The number of resource kind	WALRAS	Group method	Centralized method
10	25	16	6
20	26	18	10

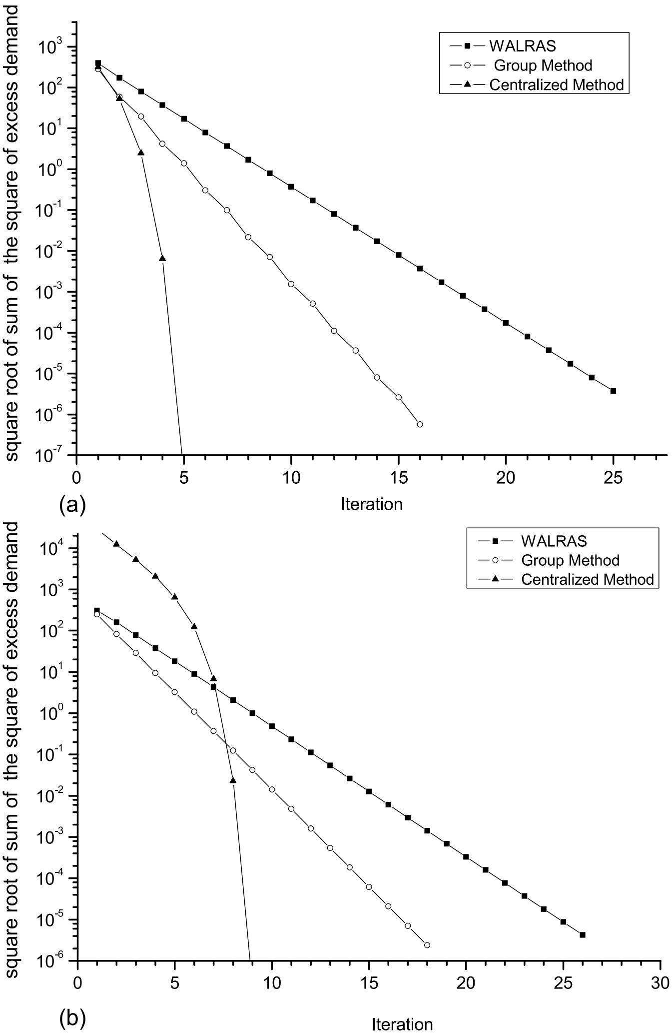


Fig. 4 The pricing process

is necessary that the distributed means is adopted. Experimental results indicate that an equilibrium can be achieved by the group pricing algorithm about 30% quicker than by the WALRAS algorithm. The rationale behind the group pricing algorithm is that not only all resources are divided into resource groups for scalability, which is borrowed from the distributed WALRAS algorithm, but also prices are adjusted simultaneously in the rang of one resource group for the quick convergence, which is borrowed from the traditional centralized pricing method.

For further comparing the group pricing algorithm with the WALRAS algorithm, the additional experiments are performed as follows.

We set $\sigma = 2$, and randomly generate the α_i coefficient from a uniform distribution [0.1, 200]. The number of resource domains is 50, and endowments for resource

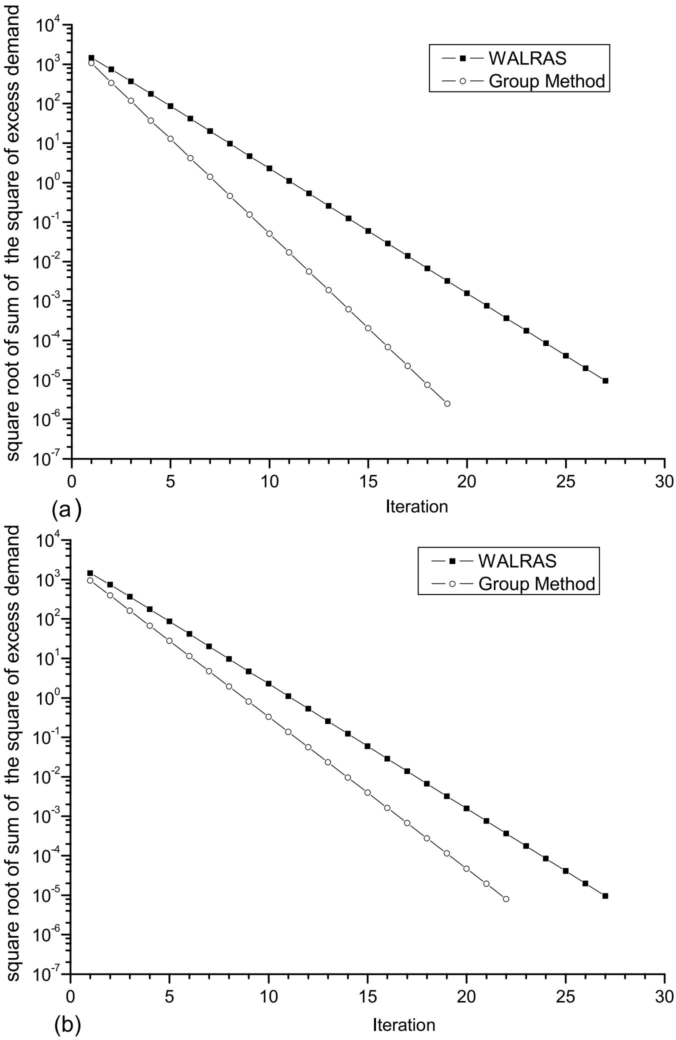


Fig. 5 The pricing process

traders are randomly generated from a uniform distribution [2000, 3000], and the total volume of each resource is randomly generated from a uniform distribution [900, 2500].

(1) The first situation is that the number of resource kind is 20. For the group pricing algorithm, resources are divided into 3 resource groups according to the degree of price correlation. The experimental result is shown as Fig. 5(a).
(2) The second situation is that the number of resource kind is 20. For the group pricing algorithm, resources are divided into 6 resource groups according to the degree of price correlation. The experimental result is shown as Fig. 5(b).

5 Double auction method for special resources

In this section, we focus on double auction for special resources in the grid context, and present a modified double auction mechanism, in which the transaction fee can be adjusted according to the practical requirement, which is different from the existing research effort [9]. For testing the efficiency, we also perform simulations.

5.1 The pricing schema

As the same as the general equilibrium method for general resources, resource traders represent resource administrative domains to express the supply and demand of resources. It is one auctioneer in the system that determines the price and the transaction volume for one special resource according to bids for the resource submitted by resource traders. It is illustrated as Fig. 6.

In this paper, we focus on the computational resource (i.e., CPU resource) in the grid context, and each resource trader will submit its biding or asking price and the supply or demand of the computational resource to the auctioneer. The auctioneer will determine the transaction price and the transaction volume according to the following mechanism.

5.2 The double auction mechanism

For one certain duration, some resource traders will play the role of sellers, and the others will act as buyers. And the role will change with time. At certain time, the number of sellers is denoted by *NS*, and the number of buyers is denoted by *NB*. In each auction round, each trader should submit two values to the auctioneer, which are the bidding or asking price for one unit computational resource and the demand or supply of computational resource. Let a_i denote the ith asking price (in the non-decreasing order) of sellers and b_j denote the jth bidding price (in the non-increasing order) of buyers, i.e., $0 \le a_1 \le a_2 \le \cdots \le a_{NS}$ (supply curve) and $b_1 \ge b_2 \ge \cdots \ge b_{NB} \ge 0$ (demand curve), which is shown as Fig. 7.

In this paper, we mainly focus on how to determine the price of computational resources through the double auction, so we assume that the demand of each buyer

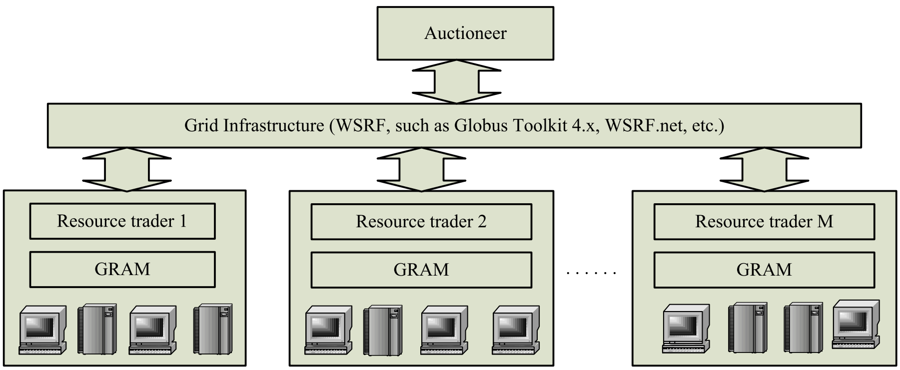


Fig. 6 The pricing schema for special resources

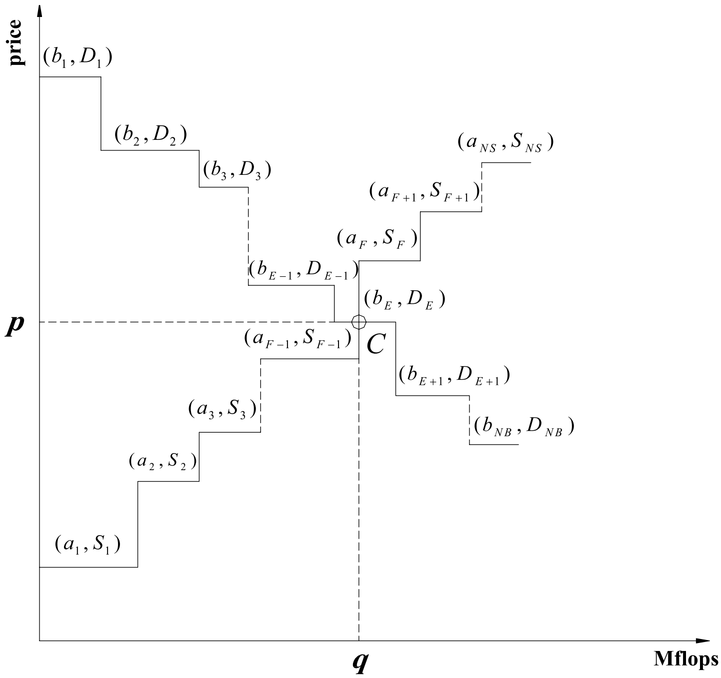


Fig. 7 An illustration of matching

and the supply of each seller for the computational resource are fixed independently at a certain value for a period. S_i denotes the supply of computational resource seller i and D_j denotes the demand of computational resource buyer j. In addition, r_j represents the marginal revenue received by buyer j for one unit computational resource, and the marginal cost c_i denotes how much it cost seller i to provide one unit computational resource.

We can determine the point of intersection $C(q, p)$ with the supply curve and the demand curve, and when the intersection of the demand curve and the supply curve is a line segment, we take $C(q, p)$ to be the midpoint of the line segment.

There are two kinds of situations for $C(q, p)$, which take the form individually as follows:

$$a_F \geq b_E \geq a_{F-1} \quad \text{and} \quad \sum_{j=1}^{E} D_j \geq \sum_{i=1}^{F-1} S_i \geq \sum_{j=1}^{E-1} D_j, \tag{2}$$

$$b_{E-1} \geq a_F \geq b_E \quad \text{and} \quad \sum_{i=1}^{F} S_i \geq \sum_{j=1}^{E-1} D_j \geq \sum_{i=1}^{F-1} S_i. \tag{3}$$

The situation of $C(q, p)$ can determine the value of E and F illustrated as Fig. 7, and seller $i(i < F)$ and buyer $j(j < E)$ will have a transaction for computational resources.

The transaction price for buyers is defined as $p^b = \max\{a_{F-1}, b_E\}$, and the transaction price for sellers is defined as $p^a = \min\{a_F, b_{E-1}\}$.

The transaction fee for seller $i(i < F)$ is defined as ϕ^a, and it satisfies:

$$p^a - p \le \phi^a \le p^a - a_{F-1}. \tag{4}$$

The transaction fee for buyer $j(j < E)$ is defined as ϕ^b, and it satisfies:

$$p - p^b \le \phi^b \le b_{E-1} - p^b. \tag{5}$$

In one auction round, the transaction volumes of sellers and buyers take the forms as follows corresponding to (2). The transaction volume V_j^b of buyer j $(j < E)$ equals to the volume of computational resource submitted by the buyer, i.e., $V_j^b = D_j$; the transaction volume of seller i $(i < F)$ is

$$V_i^a = S_i \times \left(\sum_{k=1}^{E-1} D_k \Big/ \sum_{k=1}^{F-1} S_k \right).$$

In one auction round, the transaction volumes of sellers and buyers take the forms as follows corresponding to (3). The transaction volume V_i^a of seller i $(i < F)$ equals to the volume of computational resource submitted by the seller, i.e., $V_i^a = S_i$; the transaction volume of buyer j $(j < E)$ is

$$V_j^b = D_j \times \left(\sum_{k=1}^{F-1} S_k \Big/ \sum_{k=1}^{E-1} D_k \right).$$

5.3 Mechanism efficiency and trader action

Mechanism efficiency is one important issue for designing a double auction, so we will define the mechanism efficiency of the presented double auction and test the efficiency with simulations in the follows.

For seller $i(i \ge F)$ who participates in one auction round and is unsuccessful, its utility equals to zero, and for seller $i(i < F)$ who participates in the auction round and is successful, the utility received by it is:

$$U_i^a = \left(p^a - c_i - \phi^a\right) \cdot V_i^a. \tag{6}$$

For buyer $j(j \ge E)$ who participates in the auction round and is unsuccessful, its utility equals to zero, and for buyer $j(j < E)$ who participates in the auction round and is successful, the utility received by it is:

$$U_j^b = \left(r_j - p^b - \phi^b\right) \cdot V_j^b. \tag{7}$$

Efficiency is one of the most important goals people usually pursue when designing a market mechanism. An efficient market can achieve the goal of maximizing the total profit obtained by all traders including sellers and buyers. By stronger efficiency definition, the efficiency is defined as a measure of how much all traders actually obtain compared to the maximum total market value [9].

The maximal potential total profit for one auction round is:

$$T = \sum_{i=1}^{F-1} \left(p^a - c_i\right) \cdot S_i + \sum_{j=1}^{E-1} \left(r_j - p^b\right) \cdot D_j. \tag{8}$$

The practical obtained profit of all sellers and buyers is:

$$U = \sum_{i=1}^{F-1} U_i^a + \sum_{j=1}^{E-1} U_j^b = \sum_{i=1}^{F-1} \left(p^a - c_i - \phi^a\right) \cdot V_i^a + \sum_{j=1}^{E-1} \left(r_j - p^b - \phi^b\right) \cdot V_j^b. \tag{9}$$

The efficiency of the auction mechanism is defined as:

$$EA = \frac{U}{T} \times 100. \tag{10}$$

For testing the efficiency of the presented double auction mechanism, we assume that resource traders determine their bids according to the modified version of the Roth–Erev reinforcement-learning (hereafter, referred as to MRE) algorithm, which is described in [13]. The MRE algorithm is calibrated with four parameters, a scaling parameter $s(1)$, a recency parameter r, an experimentation parameter e, and a parameter K denoting the number of possible actions that will be taken by the learner.

The MRE algorithm is summarized as follows, on which the action of sellers and buyers is based. At the beginning of the first auction round, trader i assigns an equal propensity $q_{ik}(1) = s(1)X/K$, where X is the average profit that traders can achieve in any given auction round. In addition, an equal choice probability $p_{ik}(1) = 1/K$ is assigned to each of its feasible auctions k which total is K. Trader i probabilistically selects a feasible action k' to submit to the auctioneer in accordance with its current choice probabilities. After transaction, trader i updates the corresponding parameters for next round auction according to the profit achieved in this auction round. After the nth auction round, trader i updates its existing action propensities $q_{ik}(n)$ based on its newly earned profit $R(i, k, n)$ as follows:

$$q_{ik}(n+1) = (1-r)q_{ik}(n) + ME(i, k, k', n, K, e). \tag{11}$$

ME is an updating function reflecting the experience gained from past trading activity, which takes the form:

$$ME(i, k, k', n, K, e) = \begin{cases} R(i, k', n)(1-e), & k = k', \\ q_{ik}(n)\frac{e}{K-1}, & k \neq k'. \end{cases} \tag{12}$$

Given the updated propensities $q_{ik}(n+1)$ for auction round $n+1$, updated choice probabilities $p_{ik}(n+1)$ of trader i in auction round $n+1$ is as follows:

$$p_{ik}(n+1) = \frac{q_{ik}(n+1)}{\sum_{m=1}^{K} q_{im}(n+1)}. \tag{13}$$

5.4 Experiments and results

Buyers and sellers determine the bidding price and the asking price based on the MRE algorithm, and the parameter values for the MRE algorithm are as follows. The number of possible price offers $K = 20$, the recency parameter $r = 0.1$, the experimentation parameter $e = 0.20$, a scaling parameter $s(1) = 20.0$. Correspondingly, the range of the asking price of seller i is $[c_i + 1, c_i + 20](Grid\$/1000Mflops)$, where c_i denotes the marginal cost of seller i. The range of the bidding price of buyer j is $[r_j - 20, r_j - 1](Grid\$/1000Mflops)$, where r_j denotes the marginal revenue of buyer j.

In the first experiment, the number of buyers, *NB*, is 100, and the number of sellers, *NS*, also is 100, and there is one auctioneer. And we assume that the interval of auction rounds is fixed and equal, and the auction resource is CPU resource, and the unit of the computational resource is *Mflops*. The demand and the supply are fixed for each auction run, and are distributed uniformly in the range $[1000, 10000](Mflops)$, and marginal costs of sellers and marginal revenues of buyers are both distributed uniformly in the range $[40, 80](Grid\$/1000Mflops)$. According to (4) and (5), the transaction fees are set respectively as follows:

$$\phi^a = \max\left\{\frac{2}{3}\left(p^a - a_{F-1}\right), \left(p^a - p\right)\right\}, \tag{14}$$

$$\phi^b = \max\left\{\frac{2}{3}\left(b_{E-1} - p^b\right), \left(p - p^b\right)\right\}. \tag{15}$$

The other two experiments are the same as the first experiment except that marginal costs of sellers are distributed in the range [40, 80] and marginal revenues of buyers are distributed in the range [60, 100] in the second experiment, and marginal costs of sellers are distributed in the range [60, 100] and marginal revenues of buyers are distributed in the range [40, 80] in the third experiment.

Each auction run consists of 8000 auction rounds. The experimental results are the average value of the 100 auction runs.

According to the above experiment parameters, we develop a simulator for testing the performance of the presented double auction mechanism. The results of the three experiments are shown as Fig. 8, Fig. 9 and Fig. 10, respectively.

Firstly, the standard deviation of efficiency is shown as Fig. 8(c), and the standard deviations of sellers' transaction price and buyers' transaction price are illustrated as Fig. 8(d) and Fig. 8(e), respectively. These standard deviations have small values, so that the mean of efficiency and the mean of transaction price in the experiment could reflect their general properties, respectively.

According to the efficiency outcomes of the three experiments, we can find out that the efficiency of the presented double auction mechanism is larger than 90% during the 8000 rounds in the three situations although the value varies in different rounds, and it indicates that the mechanism is efficient. According to Fig. 8(b), it can be observed that the transaction price varies mildly in different rounds. In the practical economic market, it is important that the price of resources changes gradually instead of changing discontinuously. The experimental result indicates that the mechanism can satisfy this requirement. In addition, although the transaction price of buyers p^b

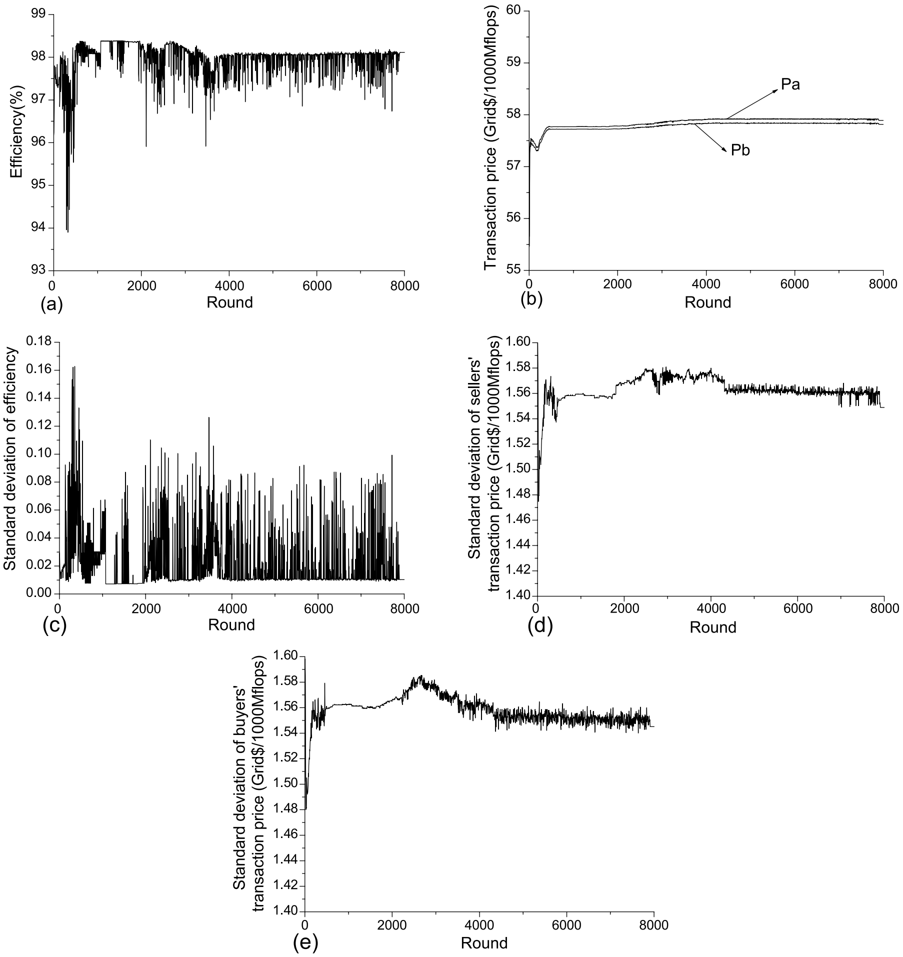
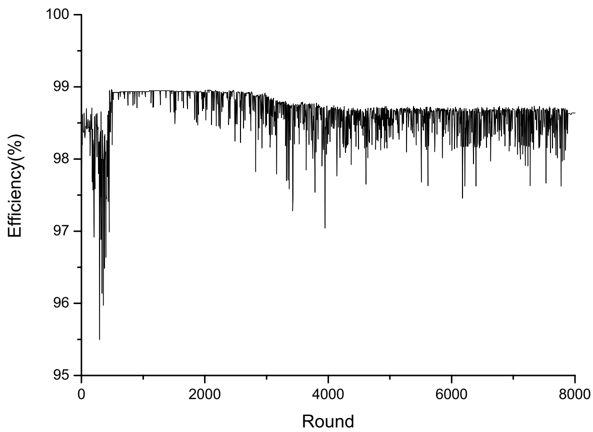


Fig. 8 The experimental result of the first experiment

Fig. 9 The efficiency of the auction mechanism in the second experiment



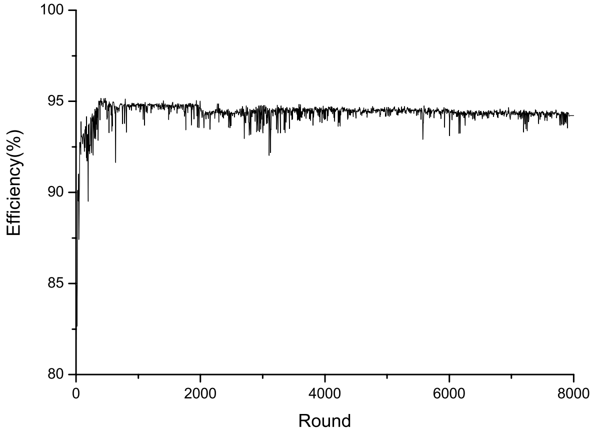


Fig. 10 The efficiency of the auction mechanism in the third experiment

is less than the transaction price of sellers p^a, the budget balance can be achieved through the transaction fee in the presented auction mechanism.

As the distribution of the buyer's marginal revenue shifts from [40, 80] to [60, 100], the efficiency outcome increases illustrated as Fig. 8(a) and Fig. 9. It could be explained that more buyers tend to offer higher bidding prices and the number of successful trading buyers and sellers increases correspondingly. As the distribution of the seller's marginal cost shifts from [40, 80] to [60, 100], the efficiency outcomes decrease illustrated as Fig. 8(a) and Fig. 10, which is expected because the number of successful trading buyers and sellers decreases correspondingly as the asking prices of sellers increase.

6 Conclusions

The research on grid computing has been performed lasting for nearly ten years. However, there are some obstacles on the road of applying the grid technology to the practice. One open problem is how to deal with resource sharing between different organizations who have their own interest.

From the perspective of resource possession, today many grid communities could be considered as *utopia*s, where grid participants are assumed to provide computational resources willingly and selflessly, which is impractical in fact. For applying the grid technology to practical applications in the industry, the economic interest should be considered.

One challenge is how to organize the resource with considering economic elements, so we propose a hierarchical framework for managing resources in the grid context, where hierarchy, virtualization and economic factors play important roles.

For meeting the diversity of resources in the grid, we adopt commodity market model and auction model for the proposed framework. The motivation of conjoining the two mechanisms for resource pricing is that commodity market model can be used to adjust the price for general resources, and auction model can be used to determine transactions for the special kind of resources in the grid context. Experimental results indicate that the two methods perform well for corresponding application scenarios, respectively.

Acknowledgements This research was supported by the National Natural Science Foundation of China (No. 90612018, No. 60473092 and No. 60503043), the National 863 Program of China (No. 2004AA104340, and No. 2004AA104280) and ChinaGrid Program of MOE of China.

References

1. Wolski R, Plank J, Brevik J, Bryan T (2001) Analyzing market-based resource allocation strategies for the computational grid. Int J High Perform Comput Appl 15(3):258–281
2. Subramoniam K, Maheswaran M, Toulouse M (2002) Towards a micro-economic model for resource allocation in grid computing systems. In: Proceedings of the 2002 IEEE Canadian conference on electrical and computer engineering, pp 782–785
3. Cao H, Xiao N, Lu X, Liu Y (2002) A market-based approach to allocate resources for computational grids. Comput Res Dev (Chin) 39(8):913–916
4. Buyya R (2002) Economic-based distributed resource management and scheduling for grid computing. PhD thesis, Monash University, Australia
5. Buyya R, Abramson D, Venugopal S (2005) The grid economy. Proc IEEE 93(3):698–714
6. Nakai J (2002) Pricing computing resources: Reading between the lines and beyond. Technical Report: NAS-01-010, NASA American Research Center
7. Cheng J, Wellman M (1998) The WALRAS algorithm: a convergent distributed implementation of general equilibrium outcomes. Comput Econ 12(1):1–24
8. Ygge F (1998) Market-oriented programming and its application to power load management. PhD thesis, Department of Computer Science, Lund University, Sweden, ISBN 91-628-3055-4
9. Huang P, Scheller-Wolf A, Sycara K (2002) Design of a multi-unit double auction E-market. Comput Intell 18(4):596–617
10. Waldspurger C, Hogg T, Huberman B, Kephart J, Stornetta W (1992) Spawn: a distributed computational economy. IEEE Trans Softw Eng 18(2):103–117
11. Regev O, Nisan N (1998) The popcorn market-online markets for computational resources. In: Proceedings of the 1st international conference on information and computation economies, pp 148–157
12. Lalis S, Karipidis A (2000) JaWS: an open market-based framework for distributed computing over the Internet. In: Proceedings of the 1st IEEE/ACM international workshop on grid computing, pp 36–46
13. Nicolaisen J, Petrov V, Tesfatsion L (2001) Market power and efficiency in a computational electricity market with discriminatory double-auction pricing. IEEE Trans Evol Comput 5(5):504–523
14. Lai K, Huberman B, Fine L (April 2004) Tycoon: a distributed market-based resource allocation systems. http://arxiv.org/abs/cs.DC/0404013
15. Chapin S, Clement M, Snell Q (October 1999) A grid resource management architecture. Grid Forum Scheduling Working Group
16. Foster I, Kesselman C, Tuecke S (2001) The anatomy of the grid: enabling scalable virtual organizations. Int J Supercomput Appl 15(3):200–222
17. Foster I, Kesselman C (eds) (2003) The grid 2: blueprint for a new computing infrastructure. Morgan Kaufmann, San Francisco
18. Czajkowski K, Ferguson D, Foster I, Frey J, Graham S, Sedukhin I, Snelling D, Tuecke S, Vambenepe W (2004) The WS-resource framework. http://www-106.ibm.com/developerworks/library/wsresource/ws-wsrf.pdf
19. Varian H (1992) Microeconomic analysis, 3rd edn. Norton, New York
20. Pindyck R, Rubinfeld D (1998) Microeconomics, 4th edn. Prentice Hall, New York