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Identifying and Modeling the Strengths and Weaknesses of Major Economic Models in Grid Resource Management

Aminul Haque · Saadat M. Alhashmi · Rajendran Parthiban

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Abstract Economic-based approaches have been found to be effective for distributed resource management in Grid computing. However, deciding which model to use is challenging, because (1) the performance stability of a particular model in a dynamic and distributed environment, is hard to establish (2) the performance objective of the Grid network may be complex, and it is difficult to know which model would best fit such an objective, (3) evidence indicates that no single model can cope with every scenario, and (4) no suitable tools exist to accurately predict and contrast the performances of one model with another model in a particular domain. Understanding the strengths and weaknesses of widely proposed economic models in terms of a range of scenarios is, therefore, crucial. To address this, the authors developed a general evaluation platform suitable for analyzing the performance of different economic models in the Grid. This work identifies domains of strength of individual models and highlights their use in various scenarios of Grid computing.

Keywords Grid computing · Economic models · Performance evaluation and comparison · Domains of strengths

A. Haque (✉)
Department of Computer Science & Engineering,
Daffodil International University, Dhaka, Bangladesh
e-mail: aminul.cse@daffodilvarsity.edu.bd

S. M. Alhashmi
College of Engineering and Computer Science,
Abu Dhabi University, Abu Dhabi, UAE
e-mail: saadat.alhashmi@adu.ac.ae

R. Parthiban
School of Engineering, Monash University Malaysia,
Bandar Sunway, Selangor, Malaysia
e-mail: rajendran.parthiban@monash.edu

1 Introduction

Grid computing makes available a network of heterogeneous computational resources (resource entities) to meet large-scale computational demand. The Grid manages the complexity associated with resource collaboration, but its effectiveness is dependent on the establishment of suitable methods for controlling and managing resources in order that a worldwide common computing platform can be made available.

As Grid resources typically belong to multiple organizations/administrations, establishing and meeting a common objective becomes challenging. Therefore, resource management and scheduling become crucial issues in the domain [1]. Several techniques including both economic and non-economic have been studied to understand the value of Grid entities [2]. As Grid entities are typically regarded as self-interested, economic-based approaches have been found to be suitable [3, 4]. First, economic-based approaches provide motivation for resource owners to contribute to the Grid, second, these approaches can help in better understanding and evaluating the needs of Grid entities and, third, they can successfully control and regulate the behavior of the entities.

The significance of economic-based resource management has been extensively studied [1, 4, 5]. Recent work identified five major economic models based on the frequency of proposals and suitability for Grid resource collaboration [6]. The models include Commodity Market, Bargaining, English Auction, Continuous Double Auction and Contract-Net-Protocol. Each of these models has its own working principle and pricing methodology, but due to the dynamic nature[1] of the Grid entities, performance by a particular model is not constant across different scenarios [6]. This ambiguity makes it difficult to decide which model to deploy. For example, the Commodity Market Model has been found to be suitable for maintaining the equilibrium between resource supply and demand, whereas the English Auction Model has been identified as being suitable for maximizing profit for providers.

No tools currently exist to evaluate and contrast the effectiveness of the models for a wide range of Grid scenarios. This paper describes the development of an evaluation platform for conducting performance analysis of the models for Grid resource management. The objectives of the study were the:

1. Development of an evaluation framework suitable for investigating and analyzing the performance of a number of widely proposed economic models for a comprehensive set of scenarios in the Grid,
2. Comparative analysis to understand the strengths and weaknesses of individual models through a clear demonstration of the domains of strength of the models for different performance metrics,
3. Formalization of the domains of strength of individual models that allow for prediction of performance in different scenarios.

The paper is structured as follows: Section 2 presents a discussion of economic-based resource management in Grid computing; Section 3 presents an evaluation framework and describes the core functionalities of the framework; Section 4 describes and models the domains of strength of the economic models; and in Section 5 the findings of this study and future research directions are discussed. The significance of the findings for economically inspired Grid communities is outlined in Section 6.

[1]Grid entities can join and leave anytime during a Grid's lifecycle

2 Literature Review

This work is an extension of [6, 7]. This section briefly describes the findings of [6] and provides the motivation for this study. The following sections focus on the experiments.

Economic models are useful for Grid resource management because they can help explain the behavior of Grid entities and predict the impact of the models on the environment. Therefore, it is important to understand the parameters that define the various models. In this study, five of the most widely proposed economic models for Grid computing, were selected. For a more detailed discussion on these various economic models, the reader may refer to Buyya et al [1].

Commodity Market Model (CMM) There are two types of CMM in the literature; one is flat pricing in which price for a resource does not vary frequently and another is supply and demand driven pricing in which the price changes very frequently depending on the market's supply and demand function. The latter is widely adopted and more popular in the Grid [8]. Thus, this work implemented the supply and demand driven CMM. The price that brings the equilibrium between supply and demand in the market is regarded as *equilibrium/spot price*.

Richard et al. propose that CMM would be suitable for maintaining market equilibrium and minimizing communication cost compared to English Auction (EA) [9]. However, Tan and Gurd criticize CMM because it is system-oriented rather than incentive-oriented [10]. They argue that in CMM, price formation process considering global information on supply and demand does not account for an individual's preference optimization; and may thus become undesirable for the participants.

Bargaining Model (BAR) BAR is one of the most widely proposed economic models in the Grid [6]. It supports negotiation between users and providers over several rounds. Such negotiation eventually helps to better understand the requirements of the market participants. The negotiation facilitates Service

Level Agreement (SLA) processes and Pareto-optimal resource allocation. Here, a user might start with a very low bid and a resource with a very high bid and the negotiation process continues until they reach mutually agreeable conditions, or until negotiations cease [1]. Negotiations may also be conducted to determine execution time or data transfer rate.

In the context of the Grid, BAR is proposed to be suitable because it supports utility-based negotiation between a user and a resource provider, and this may ultimately result in a satisfactory SLA [11]. However, the model requires a high communication demand due to its multi-round negotiation process, which might not be suitable for a large number of users in a network.

English Auction (EA) Auctions are perceived as being suitable for distributed resource collaboration among autonomous and self-interested entities [12, 13]. EA of its ascending bid type is most popular in the Grid [6]. An Auctioneer who keeps increasing the bid over rounds typically conducts the auction. Once the total number of rounds (typically pre-defined by the *Auctioneer*) finishes or no broker is willing to accept the current bid, the *Auctioneer* checks the reservation price[2] and selects a winner. The reservation price ensures that the resources are not being sold too far below their market value. The winner is generally the highest bidder. Should the auction fail, the broker can participate in another auction, thus remaining in the competition.

EA is believed to be suitable for maximizing revenue for providers, economic efficiency (Pareto-optimality in resource allocation) and QoS [3, 4]. However, the model is criticized for the fact that it is not suitable for communication and time efficiency [10]. In Grid, QoS is typically regarded as the value of service delivered to a user. This value could be measured by the flexibility in parameterization of user driven jobs, suitability of business models for different user requirements and strategies, and adaptation to changes in resource availability, capability and pricing.

Continuous Double Auction (CDA) The most popular form of CDA – open cry with order queue - has been implemented in [10]. In this form, resource costs are generated continuously until the *Auctioneer* finds a match between a *bid* (broker request) and an *ask* (resource properties). *Bids* and *asks* can be placed at any time during the auction phase. Outstanding *bids* and *asks* are maintained in an Order Book; *bid*s are sorted in descending order and *asks* are in ascending order. When there is a match, the auctioneer immediately informs the corresponding resource so that it can stop generating further *asks*. The *Auctioneer* also sends a message to the respective broker so that the Gridlet[3] can be submitted to the resource for execution. CDA has been reported to communicate efficiently and is therefore suitable for dealing with a large number of users [10, 14]. The sorting process of the model enables to expedite the resource allocation, without the need for global information.

Contract Net Protocol (CNP) CNP is popular in Grid computing, especially because it is able to support meta-scheduling and resource cooperation to deliver strong QoS to users. Meta-scheduling is a kind of scheduling process which helps to optimize preference criteria (such as minimization of execution cost and time) defined by users. A broker and a resource-node are known as manager and contractor respectively in this scenario [1]. In such a market scenario, a manager tries to optimize the scheduling process (meta-scheduling) by selecting one or more suitable contractors from available contractors in the market. The selection process is typically conducted according to the manager's preference value(s). In terms of task execution in a distributed environment such as Grid, the manager could either select time or budget to be optimized.

CNP is believed to be suitable for utility-based resource allocation and scalability [15]. It is also suitable for solving distributed cooperation problems and for supporting meta-scheduling processes. The model is specifically designed to understand users' requirements and schedule resources accordingly. Providers have a limited opportunity to optimize their utility functions in this model.

The above discussion illustrates that no single model is suitable for all scenarios in Grid resource management. There is no existing work, which clearly demonstrates the strengths and weaknesses of these models in terms of direct measure. Moreover, the

[2]The minimum price a user must pay to get access to a resource. This is basically the job execution cost by a particular node/resource

[3]Gridlet is a synonym for task

models have been studied at different points, by different researchers, using different evaluation platforms. This further emphasizes the need for a consistent evaluation processes. This paper presents a common evaluation platform suitable for analysis and contrast of the various models, in terms of their performance.

3 Evaluation Framework

This work used the GridSim tool to develop the evaluation platform. GridSim is a widely used toolkit for simulating the Grid environment [16]. GridSim runs on top of Simjava library, which provides the basis of a discrete-event simulation. The tool also supports modeling and deploys various economic-based resource management strategies. The subsequent section outlines an integral part of the framework – the Grid entities in terms of an economic system.

3.1 Economically-Inspired Grid Entities

Grid entities are typically regulated depending on their own objectives. However, economically inspired Grid entities are more complex and more self-interested in terms of defining their parameter models than compared with non-economic entities. In order to simulate such individually rational entities, proper definition of their properties is required. These properties will then play a role in defining the characteristics of the simulation.

User Grid users can be characterized using their respective applications, which then need to be executed on Grid resources. A Grid application can also be composed of several Gridlets (also known as tasks). A Gridlet can be defined as a function of several parameters and be denoted as *gl (id, length, dl, budget)*. Where, *id* = Gridlet's identity, *length* = Gridlet's processing length in MI (Million Instruction), *dl* = Deadline to finish processing the Gridlet, *budget* = Budget available to process the Gridlet. Based on the relationship and dependency among the Gridlets, Grid applications can be categorized into three types; Bag of Tasks[4] [17], MPI (Message Passing Interface) and Workflow. The current work is suitable only for Bag of Tasks-type applications. This work assumes that Gridlets have already been dispatched from an application by using a suitable dispatcher (such as Nimrod-G Dispatcher [18]) before each of the Gridlets can be sent to its corresponding broker by the user. Each broker then tries to execute its Gridlet on Grid resources within the constraints defined by the user. Future work will extend this framework to support other application types.

Broker A broker (also known as job-scheduler) performs all the crucial tasks on behalf of a user. The complete life cycle of a broker is presented in Fig. 1.

Each broker has a unique identification (ID). During the first phase of its life cycle, the broker collects the IDs of the available resources from the Grid Information Service (GIS).[5] Subsequently, it starts communicating with the resources and negotiating based on constraints as defined by the user (Fig. 1). For example, it consults with a resource to determine whether that resource can process the Gridlet within the available budget and deadline. However, the negotiation process varies for different economic models. It is worth mentioning here that in context of this paper, negotiation and bargaining have different meanings. In negotiation, it is not necessary to have iteration, however, in bargaining there must be iteration. For BAR, there are multiple iterations and revisions of the same request are being made at each iteration. For other models such CMM and CNP, the communication between a broker and a resource is assumed as negotiation in general.

The broker continuously submits its Gridlet to resources until there is a match or available resources in the market. When the broker registers a failure, it will send the unprocessed Gridlet back to the user, constituting a final rejection. If the broker finds a suitable resource, it selects the resource to submit its Gridlet. Multiple Gridlets cannot be processed on a single resource, due to the GridSim's limitations. Once the Gridlet has finished processing, the resource sends back the Gridlet to its user. Once there is a match, the agreed price is added to the provider's fund as revenue. In terms of a match, the assumption is made that the Gridlet will not be canceled from the resource, nor will the deadline be exceeded.

[4] This kind of application consists of multiple independent tasks requiring no communication among those tasks

[5] A service designed to assist Grid brokers/other entities by providing available resource information. Whenever a new resource entity is created, it is required to register with the GIS

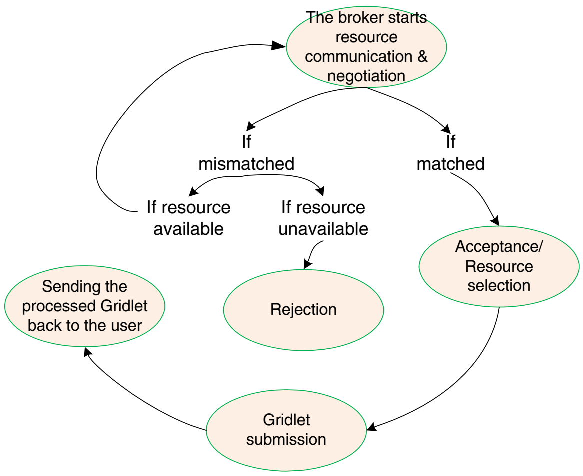

Fig. 1 A Broker's Life cycle on Gridlet execution

Resource Grid resources are typically referred to as resource-nodes or nodes. Each resource-node has several properties such as node *identity, machine-list*,[6] *allocation policy,* and *cost-per-sec* to distinguish it from other nodes. Primarily, nodes can be standalone computational and/or storage systems. Multiple organizations can join to form a network of nodes to service the requirement of a scientific application. The cost and time calculation methods for a particular Gridlet, by node, have been explained in detail elsewhere [7].

3.2 Resource Configuration and Simulation

This section explains the simulation scenarios, different simulation parameters and their statistical significance. The section also describes the fairness in evaluation among different models.

3.2.1 Grid Scenarios and Simulation Space

The Grid is dynamic in nature. In addition, market mechanisms in a Grid environment are greatly influenced by the number of users and resources (demand and supply). Therefore, to reflect on the impact of Grid dynamics, one needs to take into account a large number of possible scenarios while defining the parameter space. Grid scenarios could vary in terms of supplyand demand, application types, and application objectives. This work modeled the scenario only in terms of supply and demand. Existing literature considers only a limited number of users and resources, and varies these numbers in large steps (e.g., 5, 10, 15...), which is not comprehensive enough to understand the effectiveness of the models in the context of Grid computing. In an attempt to redress this limitation, the current work considers a parameter space consisting of a number of Gridlets and nodes, which is a 100×100 mesh of (y, x). This takes into account all possible scenarios when the maximum number of Gridlets or nodes is 100. Here, y refers to the number of nodes and x to the Gridlets. If one depicts the simulation space, it would look like Fig. 2. A value along the Z-axis represents the performance obtained for a particular evaluation metric and for a particular cell (simulation) in the space. Therefore, analyzing the effectiveness of a particular economic model for a comprehensive set of supply-demand ratios becomes feasible.

Execution of an application on real Grid resources would look like Fig. 3. Grid typically uses a dispatcher (Nimrod-G Dispatcher) to break-down an application into several Gridlets in order to facilitate the deployment of the Gridlets on multiple resources [18]. Individual Gridlets are then sent to the resources through their respective brokers for execution. The

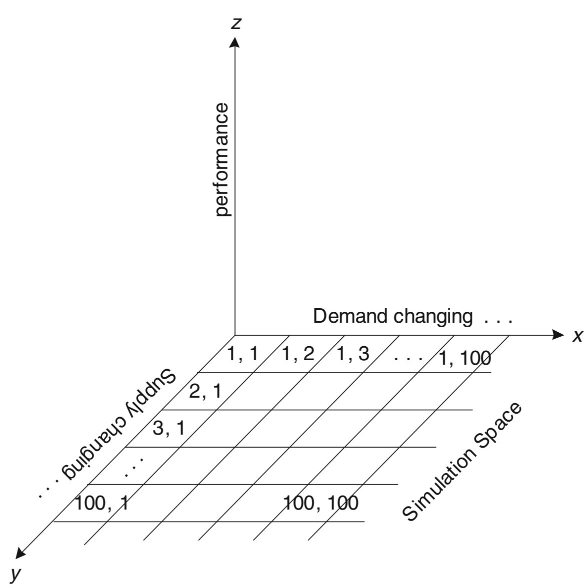

Fig. 2 Simulation space designed for the evaluation framework

[6] A node typically contains several machines and each machine may contain several Processing Elements (PEs)

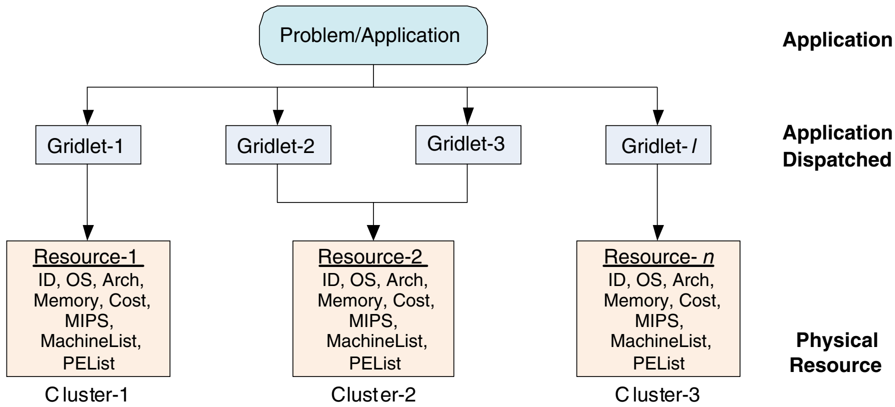

Fig. 3 Application execution environment in a real Grid

parameters for a typical Grid resource have already been described in Section 3.1. A particular resource can be used to execute one or multiple Gridlets at a time. In a Grid computing environment, each resource can be regarded as a cluster (Fig. 3); because the resource typically consists of several machines and each machine could possesses several PEs.

Figure 4 presents the execution environment in the simulated Grid. The simulation was carried out by considering an assumption that a suitable dispatcher has already dispatched the application. The simulation was conducted for a different number of Gridlets, which was up to x (100 in this case). The concept of a virtual machine rather than a real resource was assumed in the simulation. It considered that a single resource works as a single virtual machine and one virtual machine can be used to execute only one Gridlet, but the total number of machines up to y (100 in our case) can be varied. This work suggests that each virtual machine only have one PE. This helps in understanding the impact of changing supply and demand in the environment. Each virtual machine has its own ID, MIPS rating, a PE and cost of use per second. For the purpose of clarity, this paper refers to the virtual machines as resources/nodes. Currently GridSim only supports the processing of a single Gridlet, on a single PE [19]. However, several virtual machines could be under a single cluster/resource in reality and can be used for executing a single Gridlet. We would like to simulate just such an execution environment in future work. The following sub-section describes different simulation parameters and their experimental significance.

3.2.2 Simulation Parameters and Statistical Significance

Table 1 presents the parameters used to conduct the experiments. Table 1(a) presents the parameters, which were fixed throughout the simulation and Table 1(b) shows the parameters, which varied as per the ranges. This configuration is applicable for all the

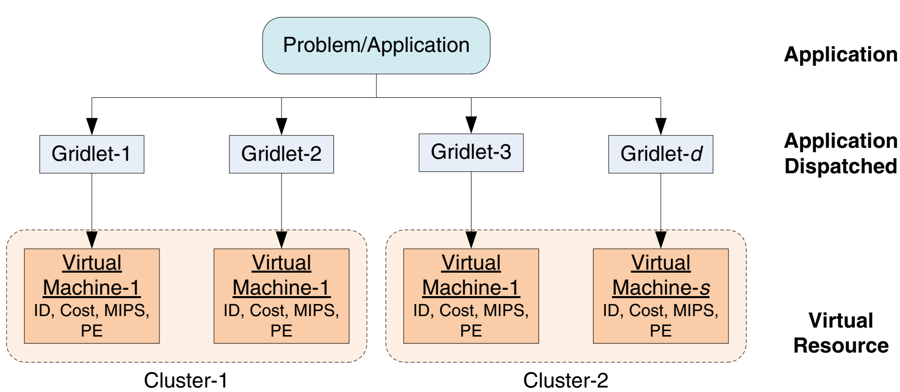

Fig. 4 Application execution environment in our simulated Grid

Table 1 Resource configuration

Parameters	Values
a. Fixed parameters	
Number of rounds (θ)	10
min-bid / min-node-bid	0
max-bid / max-node-bid	45
b. Variable parameters	
Gridlet arrival time (simulation sec.)	(5, 20)
MIPS rating for a node (in MIPS)	(350, 450)
Cost-per-sec for using a particular node (in G$ - Grid dollar) (*cost*)	(1, 2)
Gridlet length (in MI)	(1000, 10000)
Gridlet deadline (simulation sec.) (*dl*)	(12, 22)
Gridlet budget (in G$) / *max-budget*	(32, 45)
Gridlet budget (in G$) / *min-budget*	(15, 18)

five models this work is dealing with. Some parameters are only applicable for particular models. For example, the number of rounds (θ) is only applicable for Bargaining and English Auction models (please refer to Section 2).

The behavior of Grid entities is stochastic; hence, achieving the same performance at a different time with a particular model is uncertain. To minimize this uncertainty, the current work tests the models using five different distributions (samples) and presents only their averages.

The impact of economic models on Grid computing is extensive; hence, the complete evaluation of a particular model is almost impossible. However, it is better to analyze performance for as many scenarios as possible. There are several metrics to evaluate the strength of the models in Grid computing [6], including revenue, communication overhead, success rate, average turn-around time, total simulation time, resource utilization, user utility, resource utility and social welfare. This work tested the five economic models in terms of all of these metrics. For each metric, the work generated a 100 by 100 matrix. Each of its cells stored the value of the metric for the corresponding *y-x* value. For consistency, the concept of reservation price was applied for all the models.

Currency (budget) for the Gridlets was injected into the system using the limits shown in Table 1(b). This currency injection is consistent with the existing literature [20]. Broberg et al. have noted the drawbacks of having unlimited currency to the Gridlets in a simulated system [20]. Having unlimited currency could lead to starvation (domination of higher budgeted Gridlets over lower budgeted ones), and inflation and hoarding (hidden fund for future domination). These may impede proper evaluation of the models. This work used Simjava's *Random Uniform Distribution* to generate samples within the ranges shown in Table 1(b). The *seed* values in the random number generator were chosen so as to produce well-spaced sequences in order to remove correlation in the samples. This helped us to simulate the entities with configurations closer to reality. The following subsection presents the significance of this framework towards an unbiased evaluation for the models.

3.2.3 Evaluation Neutrality

The focus of this paper is to investigate and analyze the performance of widely proposed economic models in Grid computing and a consistent evaluation of the models is essential. This evaluation facilitates accuracy for a comparative analysis regarding the performance of the models. The framework developed in this work delivers valid evaluation methodology for the following reasons:

- Each economic model has been evaluated using the same parameter configuration (Table 1)
- The economic models have been implemented based only on their basic principles. No further strategic behavior has been incorporated to improve performance in a particular model
- The simulation space remains constant for all models
- The framework considers the concept of the pseudorandom approach (*seed*) for generating random values from a particular range. This consideration ensures a consistent sample generation for all models. For example, for generating the MIPS rating for resources, the range is 350, 450. Use of a particular *seed* value, for example, 7489113, to generate samples from this range, is likely to produce samples like, 378, 401, 352. As long as a generator is seeded with the same *seed* value, it would always produce the same sequence of samples. The same five seeds for different models are used to ensure evaluation neutrality

A detailed explanation of the implementation of the five economic models is outlined elsewhere [7]. For a particular economic model, this work executed 10^4different simulations. For statistical purposes, the work conducted the same simulation for five different sequences (the Random generator was seeded with five different *seed* values). For a particular model, the work conducted 5×10^4 different simulations. Likewise, the same number of simulations was carried out for the five different models.

It is beyond the scope of this paper to detail the analysis of the individual performance metrics for all the economic models, as the focus of this paper is to show a comparative overview in terms of the effectiveness of the models. The following section presents a comparative analysis of various resource management performance factors related to the models.

4 Analysis of Domains of Strength of Different Economic Models in the Grid

Economic-based distributed resource collaboration is a vast and complex topic in the Grid [6, 18]. It not only provides sufficient motivation to the resource providers to contribute their resources to the Grid but also solves the distributed scheduling problem arising from millions of requests from around the world. Therefore, understanding the pros and cons of different economic models is crucial for Grid resource providers. This work identifies a number of reasons for identifying the domains of strength of different models in Grid computing, and includes answers to the following questions:

- What are the parameters that define the strengths of an economic model?
- What are the parameters that characterize the weaknesses of an economic model?
- Which model should be used when, and for what purpose?
- What are the preferences/optimization functions of the resource providers?
- What kinds of applications do the user wants to execute on the Grid?
- Are there any preferences values that the user wants to optimize?
- What is the value of the resources that providers are delivering to the application?
- What is the structure of the Grid network and how is it characterized?

Economic models have the ability to serve the Grid from various dimensions. It helps to understand a user's QoS requirements and resource values of the providers. In the subsequent sections, the paper presents a comparative analysis of the five most widely proposed economic models to investigate their strengths and weaknesses for a wide range of performance metrics (Table 2) in the Grid.

4.1 Revenue

The revenue was computed in terms of G$ earned by the resources. For a particular simulation (a set of a supply and demand), the revenue was considered as the accumulated $ earned by all the resources relative to that simulation.

In order to identify which model (out of the five models) generates more revenue for resources, a cell wise comparison of the five matrices representing the revenues of the five models was performed. The comparison found that EA outperformed the other four models. The competition process in EA, makes it superior to the other models (refer to sub-Section 3.4 in [7]). The finding that EA is suitable for maximizing revenue for providers is compatible with that reported in the existing literature. While EA generated the highest revenue, it did produce huge communication overhead/cost. Therefore, it may be worth testing the revenue over communication cost objective function.

Table 2 Measured responses and their units

Measured responses	Unit
Revenue	G$
Revenue over communication overhead	G$
Communication overhead	Number of messages exchanged
Success rate	%
Average decision latency per Gridlet	Simulation second
Total simulation time	Simulation second
Resource utilization	%
User utility	G$
Resource utility	G$
Resource utility over communication overhead	G$
Social welfare	G$

This work normalized both parameters and manipulated revenue over communication overhead matrices corresponding to all the five models. The normalization is typically considered to neutralize the effect of two different parameters. A general normalization process is presented below.

If the revenue matrix for an economic model EM_1 is represented as $[EM_1]_{rev}$then the normalizations given as,

$$normalized[EM_1]_{rev} = \frac{[EM_1]_{rev}}{max[EM_1]_{rev}, [EM_2]_{rev}, \ldots, [EM_n]_{rev}}$$

Where, n is total number of economic models.
Similarly, for communication overhead, one can write,

$$normalized[EM_1]_{commOver} = \frac{[EM_1]_{commOver}}{max[EM_1]_{commOver}, [EM_2]_{commOver}, \ldots, [EM_n]_{commOver}}$$

Now, from an economic point of view one can think of maximizing revenue and minimizing communication overheads. Therefore, computing the normalized revenue over communication overhead ratio, one can get,

$$[EM_1]_{ratio} = \frac{normalized[EM_1]_{rev}}{normalized[EM_1]_{commOver}}$$

A cell wise comparison was then performed among these normalized matrices obtained for different economic models. The contour diagram (Fig. 5) shows the result. The contour indicates that the EA is absent, but CDA, BAR, CNP and CMM show their strengths in different scenarios.

Out of the four models, CDA shows the best performance. The maximum part of the simulation space (Region-1) is dominated by CDA. There are two reasons why CDA performed in this way. First, CDA generated the lowest communication overhead in most of the scenarios (Fig. 6). This prevented the model from lowering the revenue. Second, due to the special price formation process (*finalPrice* in [7]), the revenue earned from a particular trade lies somewhere in between the Gridlet's budget and the resource's *cpuCost*. Therefore, the ultimate revenue is neither very low nor very high. However, when the demand was sufficiently low, irrespective of the supply (Region-3), BAR outperformed all other models. Due to the high supply, Gridlets had a good chance of being able to start the bargaining with appropriate resources. Thus, the Gridlets made quick acceptance on the resources, which led to a lower communication overhead for BAR. Even in Region-3, CMM shows lower overhead compared to that of the BAR (Fig. 6).The ratio of the revenue over communication overhead is higher for BAR than that of the CMM. There are two reasons for the CMM to produce lower revenue in this region. First, the spot prices generated by CMM in this region are lower due to the high supply and low demand (sub-Section 3.6 in [7]). Thus, the job execution costs were also lower. Second, in CMM, resources were only provisioned with the original job execution costs. This prevented CMM from maximizing its revenue in Region-3.

When both the supply and demand were low (Region-4, Fig. 5), CMM tends to outperform the other models. However, due to low contribution, this region is ignored and assumed to be part of Region-3. As the supply was sufficiently low regardless of the demand (Region-2), CNP performed better than the others. CNP, in this region, produced lower communication overhead compared to that of the CDA (refer to Fig. 6). In addition, as CNP supports both time and cost optimization for the Gridlets, the decreased revenue during budget optimization could somehow be covered by the increased revenue during time optimization scenarios (sub-Section 3.7 in [7]). Therefore, like CDA, CNP produced a kind of intermediate revenue overall.

4.2 Communication Overhead

The communication overhead for a particular simulation is defined in terms of the total number of messages exchanged during the simulation.

Figure 6 demonstrates the comparison for communication overhead. There are three different regions dominated by three of the economic models – CMM, CDA and CNP. To *the strength of a particular model over other models*, it is meant that the model requires producing a lower number of messages comparatively. Because there are multiple rounds in BAR and EA,

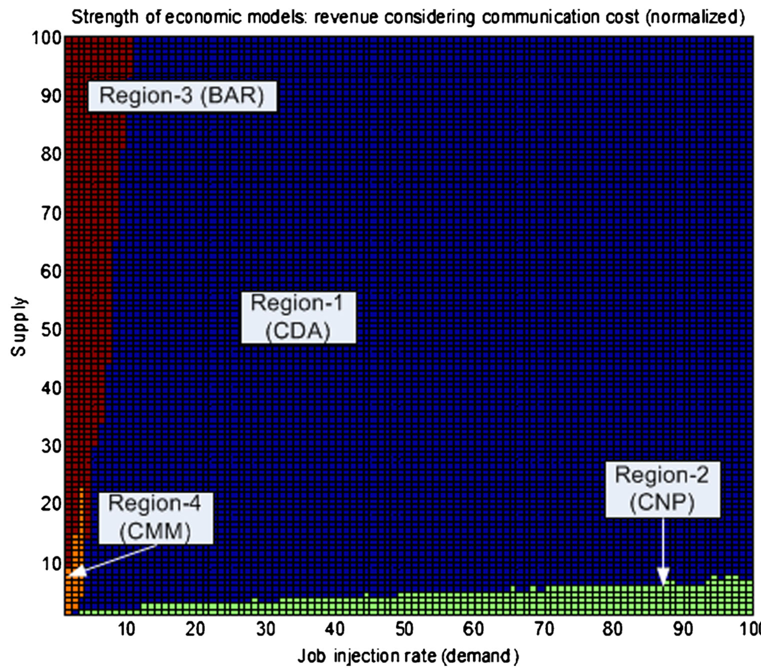

Fig. 5 Revenue comparison

even to provision a single resource, a higher number of messages was produced compared to other models. Thus, these two models are absent from the whole space.

In most of the scenarios (Region-1), CDA outperformed the other models. In CDA, resource proposals (*asks*) were submitted to the Auctioneer continuously. The Auctioneer sorted both *bids* and *asks* in way that it becomes much easier and quicker for the *Auctioneer* to match *bids* and *asks* and thus to clear the market. Fewer requests/messages, therefore, were required to be sent by a Gridlet or node into the environment.

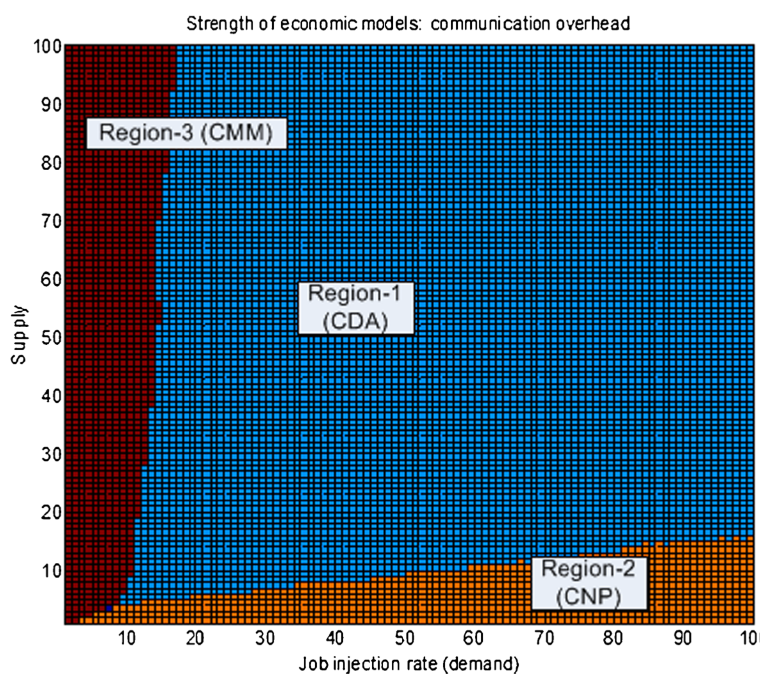

Fig. 6 Communication overhead comparison

However, when the demand was low irrespective of the supply (Region-3), CMM performed better. Due to the low demand, the spot prices generated by the model were low. This helped the Gridlets to be accepted quickly without requiring them to continuously send (look-up process) messages. As the supply increases and demand remained almost constant (the upper part of Region-3), the spot prices were lower than before. This led to quicker acceptation and helped the model to perform slightly better in this portion.

When the supply was sufficiently low regardless of the demand (Region-2), the CNP outperformed the other models. Due to the low supply, in CNP, the few nodes were quickly occupied. The strength of the CNP, in this case, can be explained by the weaknesses of other models. As mentioned earlier, due to the multiple rounds in BAR and EA, they always exchanged a higher number of messages. For CMM, the spot prices were high in this region, which means a set of Gridlets stayed in the market for a longer period of time. Finally, even the CDA is suitable for immediate resource allocation, as the nodes started generating their *asks* continuously from the start of a simulation. Even during lower supply, CDA produced a higher number of messages than does CNP. CNP therefore may be able to demonstrate its strength over the CDA, in this region.

4.3 Domains of Strengths

Revenue over Communication Cost To establish the strength for individual models, the work used the terms y and x to refer to supply and demand respectively. Each domain was formalized anti-clockwise, that is, from supply to demand. Figure 7 illustrates the formalization process for revenue over communication overhead.

Domain for Bargaining Model The first boundary that describes the domain for BAR is,

$$x = 1 \qquad (irrespective of supply)$$

The nature of the second boundary is straight and is a function of both supply and demand. The second boundary passes through 3.54, 1 and 11.15, 100. Now, the formula of a straight line passing through two coordinates *((x1, y1)* and *(x2, y2)*) is given by,

$$y = y1 + \frac{y2 - y1}{x2 - x1} \times (x - x1) \tag{1}$$

where, $y_1 = 1$; $y_2 = 100$; $x_1 = 3.54$; $x_2 = 11.15$

By substituting the values y_1, y_2, x_1, x_2 in (1), one can obtain the second boundary,

$$y = 13.01x - 46.06 \tag{2}$$

The slope m of (2) is given as,

$$m = \frac{y + 46.06}{x} = 13.01$$

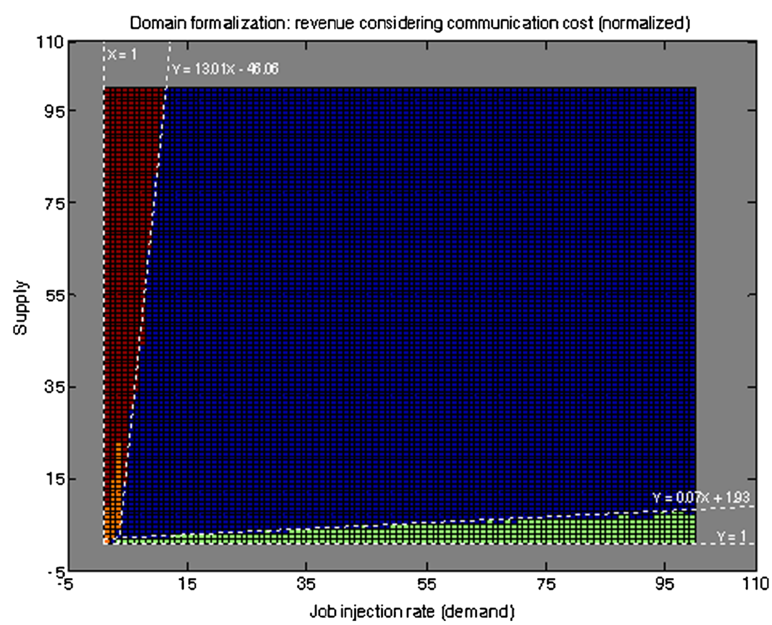

Fig. 7 Domain formalization for revenue over communication cost

Therefore, the domain is characterized as, $x \geq 1$ and $m \geq 13.01$

Domain for Continuous Double Auction The first boundary of this domain is basically the second boundary of BAR.

$$y = 13.01x - 46.06$$

For the second boundary, $y_1 = 2$; $y_2 = 9$; $x_1 = 1$; $x_2 = 100$. After substituting these values in (1), one can obtained the boundary as,

$$y = 0.07x + 1.93$$

The slopes for the first and second boundaries are,

$$m_1 = \frac{y + 46.06}{x} = 13.01 \text{ and } m_2 = \frac{y - 1.93}{x} = 0.07$$

Therefore, the domain is defined as, $m_1 < 13.01$ and $m_2 \geq 0.07$

Domain for Contract Net Protocol The first and second boundaries of this domain are,

$$y = 0.07d + 1.93$$
$$y = 1 \qquad (irrespective of demand)$$

Therefore, the domain is, $m < 0.07$ and $y \geq 1$

Communication Overhead Figure 8 presents the domain formalization for CMM.

Domain for Commodity Market Model The first boundary of this domain is straight, which is,

$$x = 1 \qquad (irrespective of supply)$$

The nature of the second boundary is not straight, rather, it is quadratic ($ax^2 + bx + c$). The equation of the closest trend is drawn as,

$$y = 0.65x^2 - 3.5x - 23 \tag{3}$$

The slope of such a parabola is typically given by,

$$m = \frac{y}{x^2} \qquad (if the vertex is at (0, 0))$$

However, as the vertex of the parabola is not at *0, 0*, a modified slope will result. From Fig. 8, one can get,

$$m = \frac{h}{w^2} Or, \quad m = \frac{h_1 + h_0}{(w_1 - w_0)^2} \tag{4}$$

This work focused only on the absolute values of h_0 and w_0. Now from (3) and (4), one can write,

$$m = \frac{h_1 + |h_0|}{(w_1 - |w_0|)^2} \tag{5}$$

To fulfill (5), one needs to know the vertex (w_0, h_0) of (3). The x-coordinate of the vertex is given by,

$-b/2a = 2.69$ where, $b = -3.5$ and $a = 0.65$ (Comparing (3) with $(ax^2 + bx + c)$)

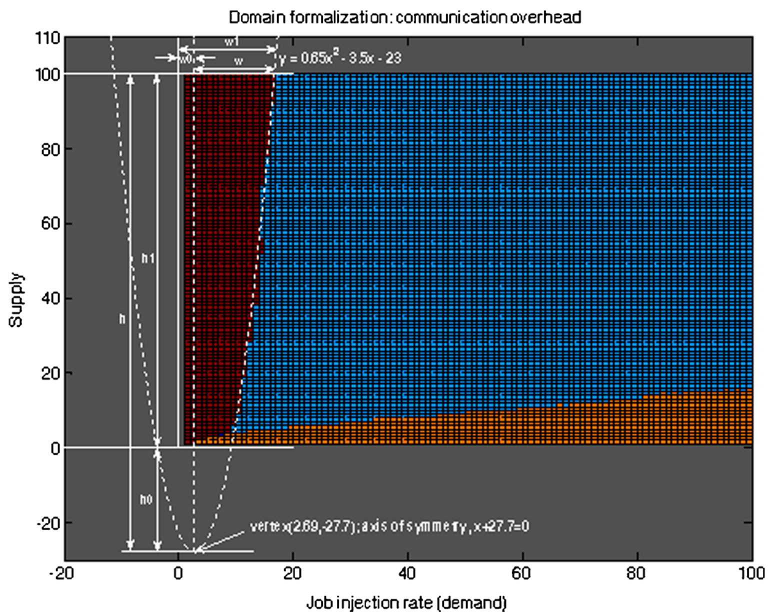

Fig. 8 Domain formalization for communication overhead-1

After solving (3) with $x = 2.69$, one can get the y-coordinate of the vertex, which is -27.7. Therefore,

$$w_0 = 2.69 \ \ and \ \ h_0 = -27.7$$

Again, $|w_0| = 2.69$ and $|h_0| = 27.7$

Now (5) gives,

$$m = \frac{h_1 + 27.7}{(w_1 - 2.69)^2} = 0.65$$

Replacing h_1 and w_1 with y and x, one can get,

$$m = \frac{y + 27.7}{(x - 2.69)^2} = 0.65 \tag{6}$$

Therefore, the domain is defined as, $x \geq 1$ and $m \geq 0.65$

Domain for Contract Net Protocol Figure 9 depicts the domain formalization for CNP. The nature of the first boundary of this domain is quadratic. Therefore, the equation is written as,

$$x = 0.32y^2 + 1.5y + 3 \tag{7}$$

The slope of this horizontal parabola is given by,

$$m = \frac{x^2}{y}$$

Once again, the vertex is not at *0, 0* From Fig. 9, one can get,

$$m = \tfrac{w^2}{h} \, Or, \qquad m = \tfrac{(w_1 - |w_0|)^2}{(h_1 + |h_0|)} \tag{8}$$

From (7) and (8), one can write,

$$m = \frac{(w_1 - |w_0|)^2}{(h_1 + |h_0|)} = 0.32 \tag{9}$$

As before, using (7), one can obtain the vertex (w_0, h_0) as,

$w_0 = 1.24$ and $h_0 = -2.34$ where $h_0 = -b/2a$

Again, $|w_0| = 1.24$ and $|h_0| = 2.34$

From (9),

$$m = \frac{w_1 - 1.24^2}{h_1 + 2.34} = 0.32$$

Now replacing w_1 and h_1 with x and y, one can find,

$$m = \frac{x - 1.24^2}{y + 2.34} = 0.32 \tag{10}$$

The second boundary is given by,

$$y = 1 \qquad (irrespective of demand)$$

Therefore, the domain is, $m < 0.32$ and $y \geq 1$

Domain for Continuous Double Auction As the domain for the CDA is enclosed by the second boundary

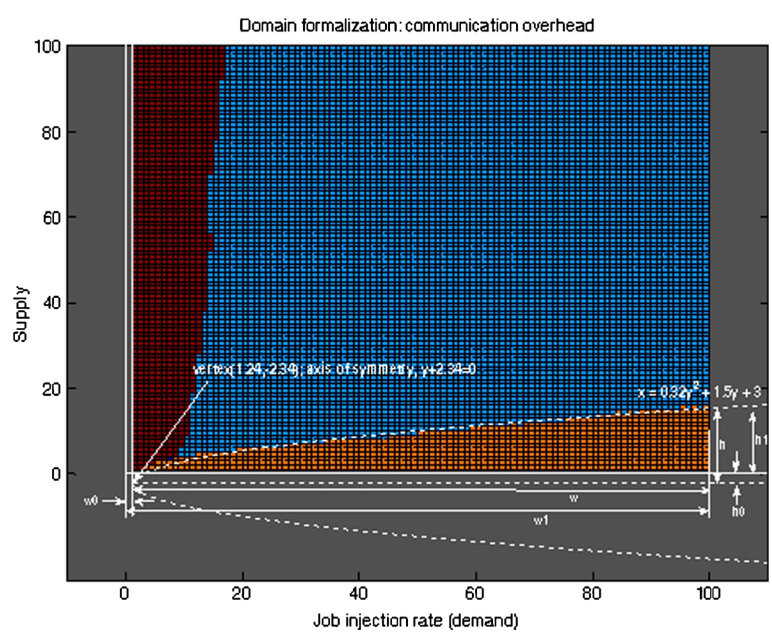

Fig. 9 Domain formalization for communication overhead-2

of CMM and the first boundary of CNP, the first slope is given as,
From (6),

$$m_1 = \frac{y + 27.7}{(x - 2.69)^2} = 0.65$$

And from (10), one can get the slope of the second boundary,

$$m_2 = \frac{(x - 1.24)^2}{y + 2.34} = 0.32$$

Therefore, the domain is described as, $m_1 < 0.65$ and $m_2 \geq 0.32$

4.4 Average Decision Latency per Gridlet

This is the average time (simulation second) required for a particular Gridlet to establish its ultimate acceptance or rejection notification.

Figure 10 demonstrates the contour diagram representing the comparison for Average decision latency per Gridlet. The CDA, CMM and BAR are the models that demonstrated their strength over different scenarios in this case. Due to limited contribution of BAR (Region-3), one can ignore this part. In terms of low demand regardless of the supply (Region-4), CMM performed better. Due to the low demand over the resources, the spot prices determined by the CMM were low. This helped the Gridlets to occupy the resources without delay. However, as the demand increases and the supply remained high (Region-1), spot prices started to rise. This forced a set of Gridlets to remain longer in the market in order to continue to search for suitable resources. This worked to the advantage of CDA which can perform better in this region as a result. Again, when the supply started decreasing and demand started increasing at Region-2, spot prices rose. This helped the higher budgeted Gridlets to be accepted quickly, which caused the other Gridlets to fail due to the shortage of resources. This results in a reduction of the average time for a particular Gridlet in CMM. As mentioned earlier, CDA is suitable for immediate resource allocation, which is another reason why the model performed better in Region-1. A similar mathematical establishment for this metric could be shown as shown in Section 4.3.

4.5 Average Decision Latency per Gridlet

Figure 11 shows the contour that represents resource utility over communication overhead. Once again,

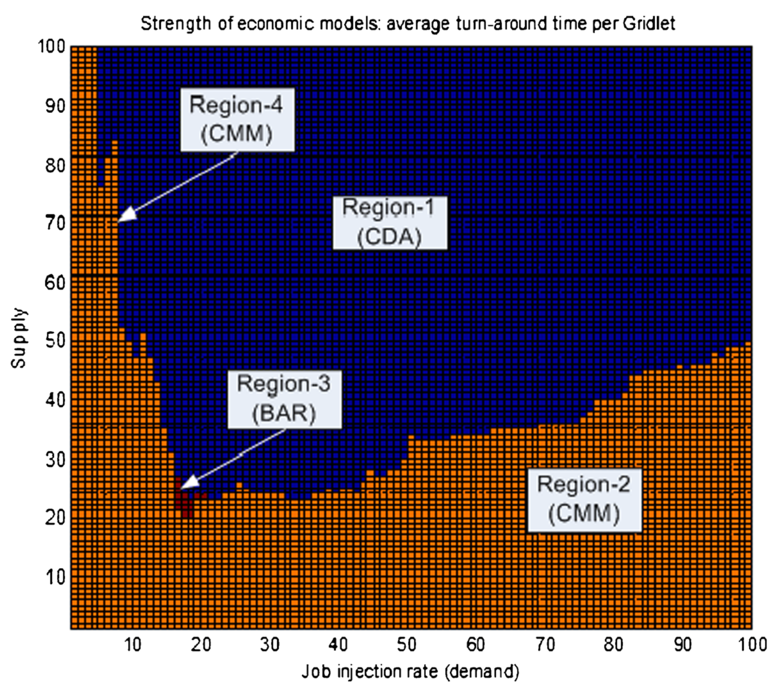

Fig. 10 Comparison for average decision latency per Gridlet

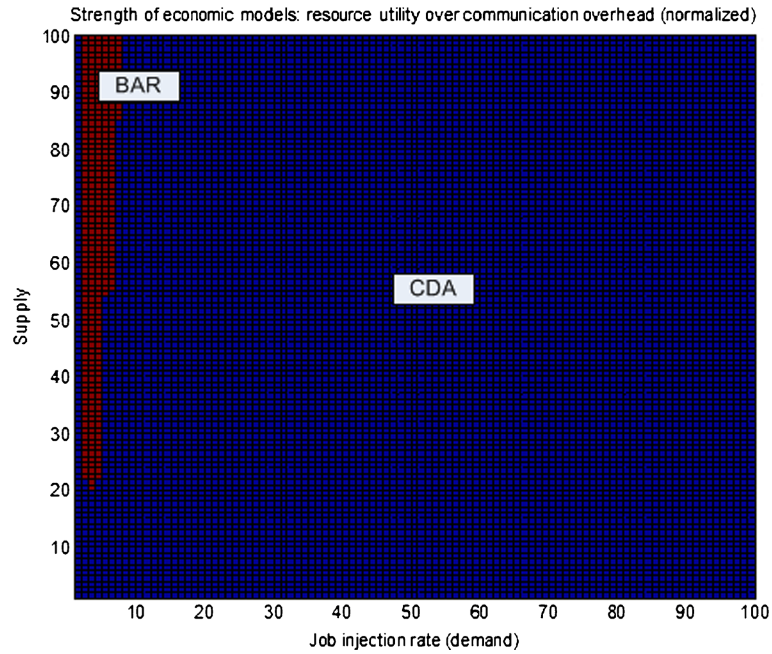

Fig. 11 Resource utility over communication overhead comparison

EA is completely absent in this measurement. The CDA and BAR are the models which dominated this space. The CDA has already been identified as one of the suitable models for minimizing communication overhead (Fig. 6). However, when the demand was low, irrespective of the supply, BAR tends to perform better. One can observe that for this particular region, CDA produced more overhead compared to the BAR (Section 4.1). Thus, comparatively, BAR received high opportunity to maximize the ratio for utility over communication overhead. However, as the supply started to decrease, the overhead produced by CDA decreased and the opportunity for BAR to negotiate with more resources decreased. As a result, CDA re-emerging and BAR began to receive lower utility.

4.6 Social Welfare

Social welfare is the combination of user and resource utilities. User/Gridlet utility is defined by the difference between a Gridlet's budget and the price the Gridlet has to pay for its execution (paid-cost). On the other hand, the resource utility is defined using the difference between the agreed price and the resource's reservation price (job-cost). The utility is represented in G$.

The contour diagram (Fig. 12) demonstrates the regions representing the strengths of different models for social welfare. In this case, it was mainly CDA and CNP that outperformed all the other models in two regions. When supply and demand were low (Region-3), BAR tends to outperform other models. However, due to its relatively small contribution, this portion is ignored. In terms of CNP, the welfare came mainly from user utility. For CDA, it came from both user and resource utilities.

When the supply was high regardless of the demand (Region-1), CDA performed better. Due to the high supply, the respective *Ask-Order-Book* is filled with low-cost resources, which means that a higher number of Gridlets with low costs are accepted (Section 3.5 in [7]). Thus, a majority of the welfare came from user utility. When the supply decreased and demand was high (Region-2), the ability of CDA to satisfying a high number of Gridlets becomes difficult, due to (1) high prices in the book and (2) shortage of resources. Even when the supply was low, CNP in Region-2 still had the opportunity to optimize user utility, which was higher even compared to the combined utility (user + resource) of CDA. As both the supply and demand decreases, the welfare for CNP/CDA decreases proportionally. Table 3 summarizes the domains of strengths formally.

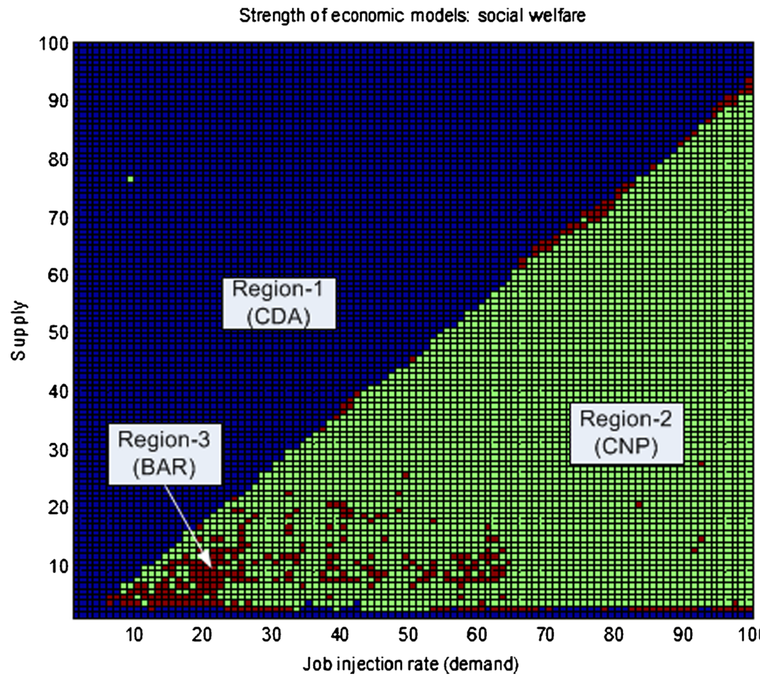

Fig. 12 Social welfare comparison

5 Discussion and Motivation for Future Research

Table 3 provides a concise representation of the geometrical definitions described above. The advantage of mathematically defining the areas is given at the end of this section.

One can observe from Table 3 that no single economic model performs well at all times. CMM has

Table 3 Domains of strengths of economic models in Grid computing

Performance metric	Economic model (Domain of Strength) space (*y, x*)
Revenue	***EA*** *(whole space)*
Revenue over communication overhead	***BAR*** $\{x \geq 1$ *and* $((y+46.06)/x) \geq 13.01\}$, ***CDA*** $\{((y+46.06)/x) < 13.01$ *and* $\{((y-1.93)/x) \geq 0.07\}$, ***CNP*** $\{((y-1.93)/x) < 0.07$ *and* $y \geq 1\}$
Communication overhead	***CMM*** $\{x \geq 1$ *and* $\left((y+27.7)/(x-2.69)^2\right) \geq 0.65\big\}$, ***CNP*** $\big\{\left((x-1.24)^2/(y+2.34)\right) < 0.32$ *and* $y \geq 1\}$, ***CDA*** $\big\{((y+27.7)/(x-2.69)^2) < 0.65$ *and* $((x-1.24)^2/(y+2.34)) \geq 0.32\big\}$
Success rate	***All Equal*** $\{1 \leq x \leq 8 \Vert 1 \leq y \leq 4\}$, ***CDA or CMM*** $\{x > 8$ *and* $((y+15)/x) \geq 4\}$, ***CDA or BAR*** $\{((y+15)/x) < 4 and y/x \geq 0.83\}$, ***CDA or CNP*** $\{0.66 \leq y/x < 0.83\}$, ***CDA or CNP or CMM or BAR*** $\{y/x < 0.66$ *and* $y \geq 4\}$
Average decision latency per Gridlet	***CMM*** $\{x \geq 1$ *and* $((125-y)/x) \geq 6.3 \Vert \left((y-22)/x^2\right) < 0.003$ and $y \geq 1\}$, ***CDA*** $\{((125-y)/x) < 6.3$ *and* $\left((y-22)/x^2\right) \geq 0.003\big\}$
Total simulation time	***CMM*** $\{1 \leq x \leq 4 \Vert ((y-9.63)/x) < 0.37$ *and* $y \geq 1\}$, ***CDA*** $\{x > 4$ *and* $((y-9.63)/x) \geq 0.37\}$
Resource utilization	*Similar to the success rate*
User utility	***CNP*** *(approx. whole space)* ***CMM*** *(negligible)*
Resource utility	***EA*** *(whole space)*
Resource utility over communication overhead	***BAR*** $\{x \geq 1, y \geq 20$ *and* $((y+90.91)/x) \geq 22.73\}$, ***CDA*** $y \geq 1, ((y+90.91)/x) < 22.73 \Vert y < 20\}$
Social welfare	***CDA*** $\{x \geq 1 and y/x \geq 0.91\}$, ***CNP*** $\{y/x < 0.91$ *and* $y \geq 1\}$

some potential for minimizing communication overhead and time. However, in terms of revenue, the model is not strong enough to compete with the other models. Even the BAR is not suitable for minimizing communication overhead; it contributes to revenue considering the communication overhead metric. The model also demonstrates its strength in the resource utility region. This implies the suitability of the model from a provider's point of view. Even EA provides the highest utility/revenue to resources, due to higher communication cost, the model becomes unsuitable for the Grid. Therefore, there is a chance that the model might be undesirable from the resource community perspective. In most of the performance metrics and a greater part of the simulation space, CDA outperforms other models. CNP, on the other hand, is also found to be suitable for revenue, considering communication overhead, user utility and social welfare performance metrics. In terms of the success rate or resource utilization, there is no single model that outperforms the other models. This indicates the variability in suitability of all the economic models except EA, across the space for this particular metric. In addition, the mathematical establishment helps identifying the scalability of the models for higher supply demand scenarios. The findings from this work demonstrate consistency with existing literature, i.e., in a highly dynamic and distributed environment such as Grid, a single model is not suitable to cope with every scenario [6]. We summarize their findings with the following statement.

There will be metrics for which one economic model, eM performs better than the others, at least not under all circumstances, G. That will depend also on the domain, g.

∃ (g) (one eM outperforms other models)

For example, in terms of communication overhead, the work has identified three different regions where three economic models (CMM, CNP and CDA) performed differently.

From the discussion above, one can identify the opportunity of optimizing different performance metrics by utilizing the potential of different models in different Grid scenarios. However, how one would be able to optimize their objective function(s) using different models in a highly dynamic environment becomes subjective. To answer this question this work draws on the following research proposals.

- This work is proposing an adaptive resource management framework that couples multiple, suitable economic models for the Grid. The framework dynamic switching between models depending on the strengths of those models. For example, if a particular Grid network has limited bandwidth and it would like to minimize its communication cost, the network can follow the findings for "communication overhead" metric. That is, if the network identifies an equal amount of supply and demand, it can use CDA (refer to Fig. 6). Again, if the network identifies that the demand has been decreased and supply is available, it can switch to CMM; because in this region, CMM generated the lowest communication overhead. Likewise, the network can minimize its overall communication cost. However, to support such framework, the broker and resource models must have adaptive capabilities to deal with different economic models.
- Realizing the dynamic and distributed nature of the Grid, the switching between models must be conducted autonomously and without any considerable delay. This work is also proposing to develop a switching agent that can sense the Grid environment and switch between models depending on the strengths required. The geometrical definitions of domains of strength in this paper made a significant contribution to the literature. By using these mathematical definitions, the agent could easily verify a suitable model for any given supply and demand ratio. This would mean that the agent would not need to import the respective matrices for making decisions - decision by cell-wise analysis can be time and computationally expensive. As the switching agent along with its roles of disseminating switching decision will be an addition in the model, the complexity of the environment will increase. We would like to study the complexity associated with the switching mechanism in future.

6 Conclusions

Economic models play an important role in the Grid in collaborating resources from distributed resource owners around the world. Therefore, evaluating the performance of different economic models in terms of a wide range of scenarios is crucial. This paper analyzed the performance of five of the most widely proposed economic models in the Grid. The evaluation methodology used was able to validly and precisely analyze the models. The method enabled us to a better understanding the performance of the models for a comprehensive set of supply and demand ratios. Through a series of experiments and subsequent identification and modeling of the domains of strength of the economic models helped to establish that different models are suitable for different scenarios. This study also identified the opportunity of developing an optimization framework through utilizing the potential of different models in different Grid scenarios. The findings in this paper make a significant contribution to the study of computational economy, by informing business strategies designed by market-based Grid providers worldwide. Importantly, this works helps to realize the potential of economic-based resource management in constructing a worldwide virtual organization.

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References

1. Buyya, R., et al.: Economic models for resource management and scheduling in Grid computing. Concurr. Comput. Pract. Experience **14**(13–15), 1507–1542 (2002)
2. Mills, K.L., Dabrowski, C.: Can economics-based resource allocation prove effective in a computation marketplace. J. Grid Comput. **6**, 291–311 (2008)
3. Beck, R., Schwind, M., Hinz, O.: Grid economics in departmentalized enterprises. J. Grid Comput. **6**, 277–290 (2008)
4. Buyya, R., Abramson, D., Venugopal, S.: The Grid economy. Proc. IEEE **93**(3), 698–714 (2005)
5. Bossenbroek, A., Tirado-Ramos, A., Sloot, P.M.A.: Grid resource allocation by means of option contracts. Syst. J. IEEE **3**(1), 49–64 (2009)
6. Haque, A., Alhashmi, S.M., Parthiban, R.: A survey of economic models in Grid computing. Futur. Gener. Comput. Syst. **27**(8), 1056–1069 (2011)
7. Haque, A., Alhashmi, S., Parthiban, R.: An inspiration for solving Grid resource management problems using multiple economic models. In: Vanmechelen, K., Altmann, J., Rana, O. (eds.) Economics of Grids, Clouds, Systems, and Services, pp. 1–16. Springer, Heidelberg (2012)
8. Stuer, G., Vanmechelen, K., Broeckhove, J.: A commodity market algorithm for pricing substitutable Grid resources. Futur. Gener. Comput. Syst. **23**(5), 688–701 (2007)
9. Wolski, R., et al.: G-commerce: market formulations controlling resource allocation on the computational Grid. In: Proceedings 15th International Parallel and Distributed Processing Symposium (2001)
10. Tan, Z., Gurd, J.R.: Market-based Grid resource allocation using a stable continuous double auction. In: 8th IEEE/ACM International Conference on Grid Computing (2007)
11. Assuncao, M., et al.: Enabling the simulation of service-oriented computing and provisioning policies for autonomic utility grids. In: Proceedings of the 4th International Workshop on Grid Economics and Business (GECON'07). Rennes (2007)
12. Parkes, D.C., Ungar, L.H.: Iterative combinatorial auctions: theory and practice (2000)
13. Xing, L., Lan, Z.: A method based on iterative combinatorial auction mechanism for resource allocation in grid multi-agent systems. In: International Conference on Intelligent Human-Machine Systems and Cybernetics. IHMSC '09 (2009)
14. Assuncao, M., Buyya, R.: An evaluation of communication demand of auction protocols in Grid environments. In: Proceedings of the 3rd International Workshop on Grid Economics and Business (GECON 2006). World Scientific Press (2006)
15. Caramia, M., Giordani, S.: Resource allocation in Grid computing: an economic model. J. WSEAS Trans. Comp. **3**(1), 19–27 (2008)
16. Buyya, R., Murshed, M.: GridSim: a toolkit for the modeling and simulation of distributed resource management and scheduling for Grid computing. Concurr. Comput. Pract. Experience **14**(13–15), 1175–1220 (2002)
17. Cirne, W., et al.: Grid computing for bag of tasks applications. In: Proceedings of the 3rd IFIP Conference on E-Commerce, E-Business and E-Government. Brazil (2003)
18. Buyya, R.: Economic-based distributed resource management and scheduling for Grid computing. Monash University, Melbourne (2002)
19. Buyya, R.: GridSim Documentation. Available from: http://www.buyya.com/gridsim/doc/faq.txt. 15 Aug 2012 (2012)
20. Broberg, J., Venugopal, S., Buyya, R.: Market-oriented Grids and utility computing: the state-of-the-art and future directions. J. Grid Comput. **6**(3), 255–276 (2008)