Modeling And Reducing Power Consumption In Large IT Systems

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Abstract – *This paper proposes a new energy optimization methodology using the Potluck Problem concept for large and complex IT systems. The proposed methodology involves analyzing the historical time-series data about resource utilization in the IT system, and finding interesting temporal patterns therefrom. Based on the analysis, a system of predictors is constructed wherein each predictor provides an estimate of demand for resources in the IT system for a future time period. These estimates are then used in the Potluck Problem solution strategy to obtain final demand predictions. This approach has been tested for efficacy using data from an actual large IT system. Before-and-after comparison is done for computing energy savings had the resources in the IT system been provisioned in accordance with our approach, in comparison with what actually transpired. Following these calculations, policies are designed with an aim to reduce the aggregate power consumption of the IT system.*

Keywords – *power consumption, power optimization, Potluck Problem, energy efficiency policies, data center energy optimization, energy demand prediction*

I. INTRODUCTION AND LITERATURE SURVEY

Large IT systems, viz., data centers and server farms, consumed about 61 billion kilowatt-hours (kWh) in 2006 in the U.S. (1.5% of total U.S. electricity consumption) for a total electricity cost of about $4.5 billion [1]. It is also estimated that the energy consumption by data centers and servers in the U.S. in 2006 is more than double the electricity that was consumed for this purpose in 2000 [1]. Taking these facts into consideration, it can be safely deduced that there is a growing need to contain the energy consumed by large and complex IT systems. Not only would this result in greener, energy-efficient IT systems but would also help in improving the financial performance of the organizations owning these systems.

In this paper, we propose a power optimization technique for large IT systems, and frame energy-efficiency policies for these IT systems using the results obtained from this technique. This power optimization technique along with the energy-efficiency policies for IT systems form the key contributions of our work. We consider a data center as an exemplar of an IT system, and CPU and disk space resources as the two main signals of the servers' activity-level in the data center. Using the Potluck Problem [2] model with multiple goods [3], we construct a prediction methodology for estimating the activity levels of the servers, as reflected in their usages of these two resources. That is, given the historical time-series data about utilization of CPU and disk resources up to time period t, we aim at determining an equilibrium or near-equilibrium condition between demand and supply of these resources such that there is no starvation and no excess of resources in the $(t+1)^{th}$ time period. Using the solution approach of the Potluck Problem, we derive predictions about the demand of CPU and disk resources for future time-periods. We then compare these predictions against the actual demand for resources (for the period between August and October, 2009) so as to compute the accuracy of these predictions. Having obtained significantly accurate estimations about the demand for CPU and disk resources in the data center, we go on to derive any energy savings that might have accrued, had the data center been allocated these resources in accordance with the predicted utilization levels. We found that using the said estimation methodology could have yielded 20–35% energy savings in the data center.

It is also observed that certain CPU/disk utilization patterns repeat themselves over long periods of time, but in ways that may not be apparent at the application level. Using these observations and the estimated demand for resources, we frame data center design-level and day-to-day operational policies that could guide resource provisioning and utilization in the data centers and other similar IT systems, thereby helping in keeping the energy costs of the data center in line. The effectiveness of these policies, in terms of energy savings, is also analyzed.

Various methodologies have been proposed for reducing power consumption in data centers and server clusters. Moore et al. [4] present methods for collecting and analyzing workload data from data centers in a automated manner. They also propose workload playback methods which allow for emulation of sophisticated workloads in data centers. Heath et al. [5] illustrate the design mechanism of a heterogenous server cluster that can adjust its configuration and request distribution so as to reduce power consumption by the cluster. Rajamani and Lefurgy [6] also present request distribution schemes, based on system and workload factors, for server clusters with an aim to reduce the energy consumption of the clusters. Contributions have also been made in the field of resource provisioning in IT systems. Chase et al. [7] present a framework architecture for managing resources in an Internet hosting center system such that the power consumption of the system is optimized by using techniques like automatically adapting to offered workload, re-

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sizing the power-on server set, etc. Similar work has been done in [8] wherein Doyle et al. propose an approach to manage resources in a web service utility, focusing primarily on network and storage resources, so as to improve service quality and performance goals. Fan et al. [9] discusses power provisioning in a large IT system. Villela et al. [10] explore how Web service providers can allocate application tier resources among their customers so as to maximize profits. Other related research works are by Gmach et al. [11], [12], which present workload analysis and prediction methodologies for data centers, and Vercatauren et al [13], who do the same for web servers.

This paper is organized as follows. Section II explains how data center resources' prediction problem is modeled as a Potluck Problem. Section III provides analyses of the servers' utilization data which is then used for building predictions about the demand of CPU and disk resources in the data center. Section IV describes how the solution strategy proposed in the Potluck Problem is used to predict the aggregate demand for data center resources. Section V validates these predictions and formulates energy-efficiency policies for the data centers. Section VI draws the conclusions.

II. PROBLEM STATEMENT

We focus on CPU and disk resources of a data center and consider them as components playing a significant role in the power consumption of servers belonging to the data center. Given the historical time-series data about utilization of these two resources for the past t time periods, the objective is to estimate the total demand for these resources in the $(t+1)^{th}$ time period so that the quantity available in the $(t+1)^{th}$ time period can be controlled/tweaked (as per the predicted demand) with a purpose to achieve an equilibrium between demand and supply of the data center resources. The equilibrium state, in the context of the resources in the data center, implies no idle resources and no lack of resources in the data center at the $(t+1)^{th}$ time period. In practical scenarios, however, certain data centers might follow a policy of having a *fixed* redundancy factor, say 5–10% with respect to computing resources in order to cater to situations of load spikes in the data center. In our computations, we include 10% redundancy factor in the estimated demand for data center resources.

In the equilibrium state, the power consumption of the data center would be at an optimum level as all the idle resources, which were not being utilized but nonetheless were consuming power, are excluded from the system. In doing so, the operational efficiency of the data center users is not compromised as there is no starvation of resources in the equilibrium state.

The demand for CPU and disk resources in a data center varies over time owing to factors like new workloads being allocated to certain servers, time-based low utilization periods, etc., making it hard to predict the exact demand at a particular future time. We assume that the supply of these resources is controlled and can be varied by data center administrators or other appropriate authorities with the purpose of optimizing the resource utilization and minimizing the power usage of the data centers. In order to predict the demand for data center resources, we use the Potluck Problem [2] concept. The Potluck Problem deals with resource allocation in a multi-agent non-cooperative system, and is a generalization of the Santa Fe Bar Problem (SFBP) [14].

III. DATA USED AND ITS ANALYSES

We have used data about more than 715 actual servers of a data center for analyses and demand prediction of resources. The data describe different aspects of physical utilization of these servers, with CPU utilization and disk utilization being two of them.

The CPU and disk utilization data is obtained from an agent-based software system running on the OS of each of the servers in the data center. We retrieve the CPU and disk utilization data for each server in the data center with hourly granularity (i.e., average CPU/disk utilization over 60 minutes interval across all CPUs and disks for each server), and aggregate it to find daily, weekly and monthly CPU and disk utilization for the servers. The servers taken into consideration are classified into three categories based on characteristics like hardware model, operating system, etc. Category A, B and C have $\sim$ 200, 350 and 165 servers respectively. (The exact numbers vary slightly with time in somewhat irregular fashion due to upgrades, maintenance, breakdowns, etc.)

Having computed the average CPU and disk utilization of the data center servers, we proceed to find an approximate measure of the power consumed by the data center in the same time period. In order to do so, we use the power model described in [5] which relates resource utilization to its corresponding power consumption in the following manner:

$$P_i = W_i + \sum_r M_i^r \times \frac{U_i^r}{C_i^r}$$

where P_i = power consumed by machine i,
W_i = base power consumed by machine i when it is idle,
M_i^r = measure of the power of resource r at full utilization,
U_i^r = utilization of resource r on machine i, and
C_i^r = capacity of resource r on machine i.

In order to calculate the approximate power usage of the servers in Category A and Category B, we assume (for the sake of simplicity) that the servers in each category are homogeneous and that the variables in the power model assume the following (realistic) values:

W_a = 100 watts, where machine $a \in$ Category A,

W_b = 105 watts, where machine $b \in$ Category-B,

M_a^{r1} = 70 watts, where $r1$ denotes CPU resource

M_a^{r2} = 16 watts, where $r2$ denotes disk resource

M_b^{r1} = 80 watts, M_b^{r2} = 12 watts,

$C_a^{r1}, C_a^{r2}, C_b^{r1}, C_b^{r2}$ (in %)=100, as the entire CPU and disk is available for usage when the server is in power-on state, $U_a^{r1}, U_a^{r2}, U_b^{r1}, U_b^{r2}$ = CPU and disk utilization values (in %) as retrieved from the data source.

Using the above methodology, we compute the power consumption of the servers (that belong to Category A and Category B) in the data center. 1 and 2 display the CPU utilization, disk utilization and, the corresponding power usage of the servers in Category-A and Category-B. The X-axis shows the week numbers from April 1 to October 31, 2009. The primary Y-axis displays CPU and disk utilization in percentage and the secondary Y-axis displays the energy consumption of the servers in kWh.

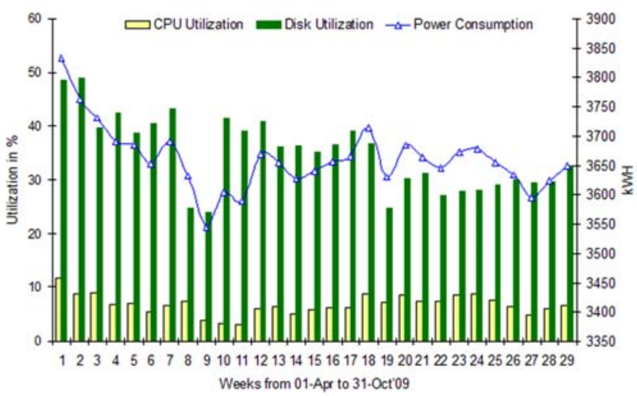

Fig. 1. CPU, Disk utilization and Power Consumption in Category A from April to October 2009

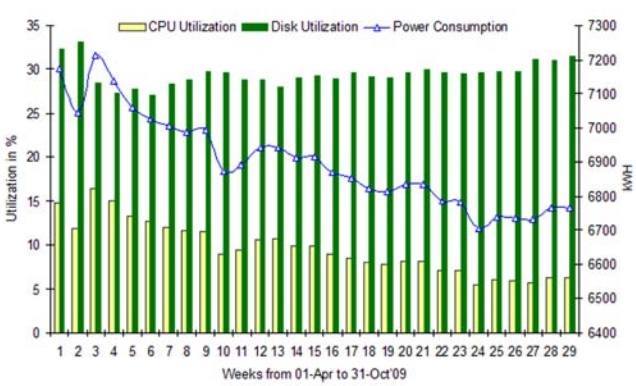

Fig. 2. CPU, Disk utilization and Power Consumption in Category B from April to October 2009

IV. Solution Strategy

A. Modeling Resource Utilization In Data Centers As A Potluck Problem

We consider CPU and disk resources of data centers as two individual non-consumable goods which are available to the users of data centers for allocation. There are two kinds of roles to be played by different entities: one that deals with the supply of the goods, and another that deals with the demand or consumption of the goods. Since the servers supply CPU and disk resources in the data center, we call them the *supplier agents*. Along similar lines, we refer to each user of the data center as a *consumer agent*, since the users are the ones for whom the CPU and disk resources are allocated. A time instance t at which the resources offered by the supplier agents are allocated to the consumer agents is considered as a potluck dinner instance. Such a potluck dinner instance can be scheduled to take place, say, every 10 minutes, every hour, every day, etc. At the dinner instance, each supplier agent individually contributes a certain quantity of each good to the dinner. There is no cooperation or collusion among the supplier agents regarding the quantity of goods to be supplied at any dinner instance.

We denote the quantity supplied by the supplier agent i at instance t as $s_{i,t}$, and the quantity demanded by the consumer agent j at instance t as $d_{j,t}$. A dinner instance is considered "enjoyable" if there is no starvation or excess of resources at that instance, i.e.,

$$\sum_j d_{j,t} = \sum_i s_{i,t}.$$

Starvation implies a situation where the aggregate supply $\sum_i s_{i,t}$ of resources in the data center is less than the aggregate demand $\sum_j d_{j,t}$. This can be interpreted as a situation where there are not enough resources provisioned in the data center at instance t due to which the operational efficiency of the consumer agents is hampered. On the other hand, excess at a particular instance implies that there are more resources than are actually required at that instance. This can be interpreted as a situation where there are idle resources in the data center which add to the power usage of the data center without getting utilized.

We aim at obtaining a perfect or near-equilibrium state where the aggregate demand of goods is absolutely or nearly equal to the aggregate supply. In order to reach an equilibrium or near-equilibrium state between demand and supply at an instance t, each supplier agent, using the solution strategy of the Potluck Problem, predicts the demand of resources for the t^{th} dinner instance, and based on this prediction, decides on the quantities to supply at the dinner instance. The higher the accuracy of these demand predictions by the supplier agents, the closer we get to the equilibrium between aggregate demand and supply of resources in the data center.

B. Predicting The Demand For Resources

Given the historical time-series data about utilization of CPU and disk resources for the past t instances, we now go on to predict the demand for these goods in the $(t+1)^{th}$ instance using the solution strategy proposed in the Potluck Problem. We first construct predictors that are capable of estimating demand for the two data center resources in question. As suggested in [3], the nature of goods tend to influence their demand structure. For instance, if the two goods in consideration are perfect substitutes of each other, then the optimal choices for each of them can be predicted using the utility function: $u(x_1, x_2) = ax_1 + bx_2$ where a and b indicate the value of x_1 and x_2 to the consumer.

The CPU and disk resources can, to a certain extent, be thought of as complementary goods. Keeping this relation and other factors in mind, the following predictors are constructed for estimation of the demand of the two resources:

1. average weekly/monthly disk utilization as related to average weekly/monthly CPU utilization;
2. n^{th} weekday's CPU/disk utilization as related to $0 - x\%$ of average CPU/disk utilization on the past y weeks' n^{th} weekday, where x is a tunable parameter;
3. average weekly disk utilization as related to average weekly CPU utilization of past n alternate weeks;
4. average utilization of CPU/disk on n^{th} weekend as related to average CPU/disk utilization on the past j weekdays; and
5. other variations of the above, based on different statistical and time parameters.

Once these predictors are built, we train these predictors using data sets for the past t time-periods. This helps us determinine the accuracy and effectiveness of each of the predictors. We then go on to use these predictors in the weighted majority algorithm [15] to predict the final demand of CPU and disk resources for $(t+1)^{th}$ time-period. It is observed that these predictions are reasonably close/accurate indicators of CPU and disk resources' demand levels in the data center, as is shown in Figures 3 and 4. In these graphs, we display the predicted demand as compared to actual demand for CPU and disk resources over a time-period of 3 months (August to October 2009).

The accuracy rate of these predictions can be further improved by following detailed factor analysis mechanisms for the demand of CPU and disk resources. It should be noted that adding a good predictor to the system of predictors in the Potluck Problem model improves the final estimations, but that if a bad predictor is added to the system of predictors, it would not bring down the accuracy factor of final estimations significantly because with each iteration (or the dinner instance), the poor predictor provides inaccurate demand estimates, as a result of which the Potluck Problem algorithm reduces the weight assigned to this predictor. After a small number of iterations, the weight of this predictor is reduced to such an extent that it no longer has an impact on the final estimates provided.

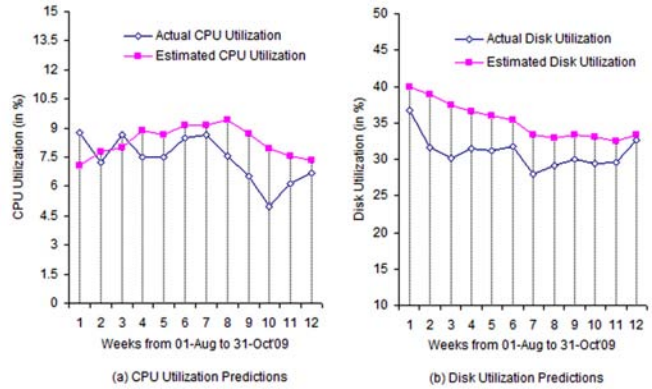

Fig. 3. CPU, Disk Utilization Predictions in Category A from August to October 2009

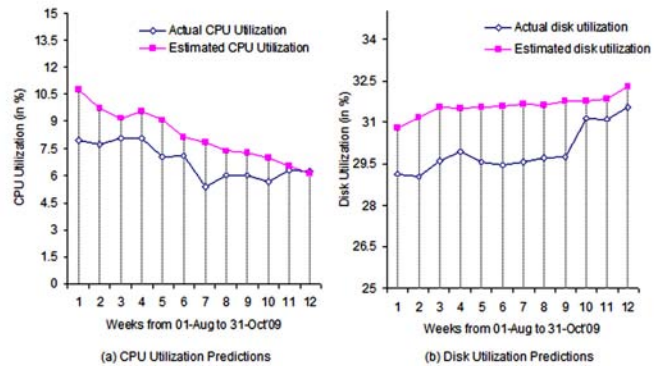

Fig. 4. CPU, Disk Utilization Predictions in Category B from August to October 2009

C. Estimating Energy Savings In A Data Center

Having obtained reasonable demand predictions for CPU and disk resources in the data center, we now go on to derive an estimation of energy savings that might have accrued had the computing infrastructure usage/provisioning in the data center been in accordance with these predictions. We assume that the CPU and disks in the server systems in Category A and Category B have the configurations shown in the Table I and II:

TABLE I. Configuration in Category A

Component	Count	Peak Power
CPU	1	80W
Disk	1	12W

If the amount of computing resources required by the data center in future time periods could be known in advance, then the data center administrators could reduce the total amount of power dissipation via idle servers by allocating only the required number of server systems to the data center. Our predic-

TABLE II. Configuration in Category B

Component	Count	Peak Power
CPU	1	70W
Disk	1	14W

tion methodology serves this purpose by providing reasonably accurate estimates of the demand for computing resources in the data center. If the server systems are provisioned for the t^{th} time period in accordance with the predicted demand, then significant energy savings can be achieved by switching the excess servers to any low-power-state mode. The next section brings out the differences in the power consumption before and after using the Potluck Problem solution strategy.

While estimating the number of CPU and disk resources required in the data center for any time period, we have taken care that no CPU or disk resource is excessively utilized, i.e., CPU and disk utilization of any server should not exceed 80% and 85% respectively.

V. ANALYSES RESULTS

Based on our prediction methodology and power model, we derive the power savings shown in Figures 5 and 6. The estimated power savings are between 20–35% for Category A and Category B. This range of power savings differs for different categories of servers due to differences in their workload mix, usage patterns, etc. While computing these estimation figures, we have factored in 10% threshold for redundant servers that might have to be kept in the power-on mode in the data center at any point in time so as to cater to the sudden spikes in demand.

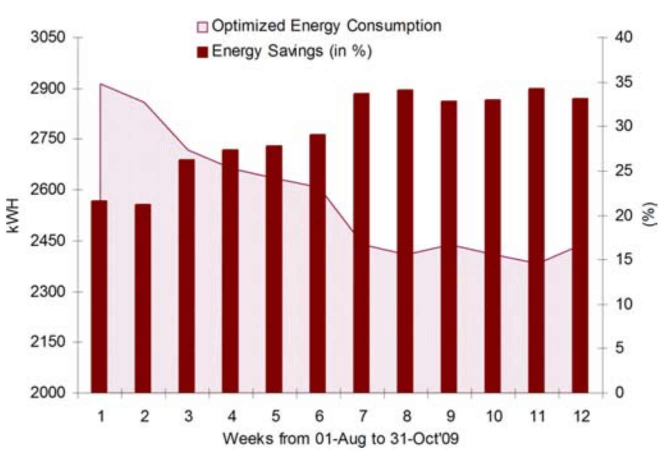

Fig. 5. Optimized Energy Consumption in Category A from April to October 2009

We found that the demand of CPU and disk resources (for the August to October, 2009 time period) could be satisfied with powering up only approximately 60–65% of the total

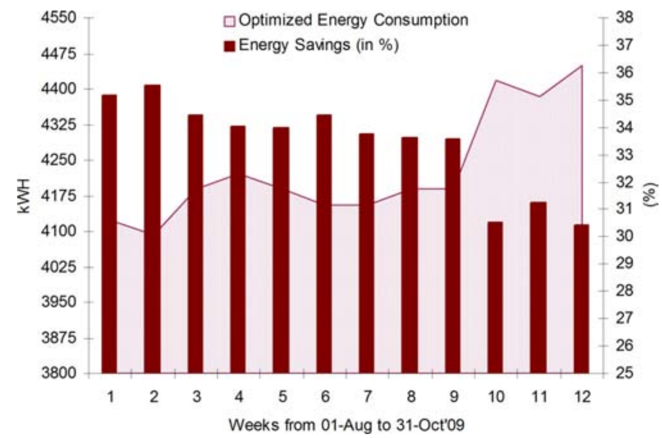

Fig. 6. Optimized Energy Consumption in Category B from April to October 2009

number of servers in the data center. This indicates a need to have cohesive set of energy efficiency policies for data center power management. Using the insights gained from our analyses, we now frame design-level and day-to-day operational policies that could lead to a reduction in the overall cost of powering server systems in the data centers. We also derive estimations of energy savings that could accrue from each of the policies.

A. *Design-Level Policies*

Taking the data analyses and predictions into account, an energy efficiency policy can be framed as follows: computing equipment which has CPU utilization $\leq 4\%$ and disk utilization $\leq 8\%$ for a consecutive time period of 6 months or more should be decommissioned from the data center. The resultant energy saving in our data center from the implementation of this policy is estimated to be $\sim$9%. Apart from the direct energy savings resulting from no power drawn from the decommissioned servers, this policy would also lead to reduction in the server footprint of the data center which, in turn, has multifold benefits like, better utilization of the floor space, reduction in the cost of powering (and maintaining) cooling infrastructure and, in the long-run, deferment of costly investments in the new data centers.

Another data center design policy deals with identifying certain high-capacity servers which have CPU utilization $\leq 10\%$ and disk utilization $\leq 20\%$ for the past 6 months or more consecutively, and reconfiguring them for virtualization such that they could host multiple virtual servers, thus increasing their utilization. As a result, workloads of a number of smaller physical servers can be allocated to the virtual servers and the freed-up physical servers can be switched off thus, reducing the overall power consumption of the data center. Alternately, the freed physical servers can be reprovisioned appropriately to carry out other workloads.

B. Operational Policies

Based on the CPU and disk usage patterns over specific time intervals, we frame daily/weekly policies aiming at reducing the energy consumption of the data center. Our analyses show that one of the most effective policies for server systems is to shut-down (or switch to low-power states) those machines that have the average CPU utilization $\leq$8% and disk utilization $\leq$21% and peak CPU utilization $\leq$14% and disk utilization $\leq$15%. The energy savings from this policy in our data center are estimated to be 20–28%. Similar polices can be devised for servers in other categories, based on different statistical and time parameters.

One might argue that it may not be practically feasible to shut-down (or even switch to low-power modes) servers in the data center as the server systems might be hosting production-environment client applications with service-level agreements associated with them. In our study, we noticed that out of 715 servers, only a small fraction of servers host such business-critical applications; the rest of them are primarily used for application development and testing purposes. Hence, the enforcement of the above-mentioned policies can be done on these machines without any service-level agreement violations.

The estimated energy savings resulting from these data-center-level power policies do not include the reduction in cooling and other ancillary costs that would result from decommissioning and consolidation of physical servers in the data center. If the computing machinery in the data center is provisioned using our estimation methodology, then the existing data center infrastructure can be optimized and the cost of powering cooling equipment like air conditioners, etc., can also be reduced significantly. This can in turn help in avoiding to build new data centers which are costly investments.

Having designed the data center power management policies and estimated the energy savings resulting, we turn our attention to the enforcement of these policies and emphasize that the enforcement must be done in consistent fashion in the data center. It is well known that change management in data centers is a tedious task and requires business processes to be followed and approvals be taken from various levels in the organizational hierarchy. But since these power policies can yield significant and recurring cost savings to the organization, the effort required in the enforcement of these policies must be given due importance.

VI. CONCLUSION AND FUTURE WORK

In this paper, we proposed a methodology for reducing the power consumption of large IT systems. In the process, we modeled the optimization of resource allocation in an IT system as a Potluck Problem with multiple goods and used its solution strategy to arrive at resource usage predictions for future time periods. We illustrated, using a data center as an exemplar of an IT system, how these predictions could guide the provisioning of resources in the IT system such that the power consumption by the system is optimized and the overall energy cost of operating the system is reduced.

In the current work, the model used for server utilization takes into consideration only CPU and disk resources. However, there are other components of a server (e.g., memory, fan) which too have a significant share in the power consumed by it. In future work, this server utilization model can be expanded to include the other components of a server too, such that the predictions based on this model are more generic and closer to reality. Also, the policies framed in this paper can be improvised to include factors that, in actual production environments, influence the actuation of the policies (e.g., server criticality, functional interdependencies of servers, etc.). Over a period of time, the policies which are most effective in saving the energy of the IT system can be generalized to construct a holistic policy framework for an IT system.

VII. ACKNOWLEDGEMENT

The author Nidhi Singh would like to thank Alan Hartman for his comments on this work.

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