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Thermal-aware relocation of servers in green data centers

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Abstract: Rise in inlet air temperature increases the corresponding outlet air temperature from the server. As an added effect of rise in inlet air temperature, some active servers may start exhaling intensely hot air to form a hotspot. Increase in hot air temperature and occasional hotspots are an added burden on the cooling mechanism and result in energy wastage in data centers. This may also result in failure of server hardware. Identifying and comparing the thermal sensitivity to inlet air temperature for various servers helps in the thermal-aware arrangement and location switching of servers to minimize the cooling energy wastage. The peak outlet temperature among the relocated servers can be lowered and even be homogenized to reduce the cooling load and chances of hotspots. Based upon mutual comparison of inlet temperature sensitivity of heterogeneous servers, this paper presents a proactive approach for thermal-aware relocation of data center servers. The experimental results show a cooling energy saving by as much as 2.1 kWh, lowering the chances of hotspots by over 77% and helps the establishment of green data centers.

Key words: Servers, Green data center, Thermal-aware, Relocation
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1 Introduction

Data centers around the world consume an enormous amount of electric power each year. An average data center consumes the equivalent amount of electricity as 25,000 homes in U.S.A. (Assure, 2011). The cost of electricity expenditure exceeds the total capital expenditure over the working life of servers. Apart from computing, a major amount of electricity is also consumed in cooling the servers. This is because a data center has a closed environment and the electrical power consumed by IT equipment is converted into heat (GmbH) and an equal amount of power is needed to remove that heat and to maintain a proper working environment via cooling. Data centers must apply energy saving techniques to go green as a large part of the electricity is generated by burning fossil fuels. Considering the hot/cold aisle rack arrangement over raised floor design of a data center (EPA, 2007), the cooling cost can be as much as the computing cost in terms of electricity used.

Power Usage Efficiency (PUE) is the ratio of total electricity usage by the data center to the electricity used for computing. If the cooling infrastructure consists of mechanical chillers only (Liu *et al.*, 2012), then the PUE value may be equal to 2.0 unless power saving practices are adopted. Recent studies have shown a little decrease in data center PUE worldwide to 1.93 (Koomey, 2011). The traditional approach of server consolidation to save computing power may result in utilization of few servers to their limit. But the electricity consumption and the resulting heat dissipation from these servers reach to maximum in a small area of the data center. Rise in inlet air temperature can further increase the outlet temperature to such a limit that a hotspot is formed. A hotspot may trigger the otherwise idle cooling mech-

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anism to start cooling or it may prolong the cooling process for an already active cooling mechanism. In both cases, the cooling is boosted for a larger area than that of the hotspot and more power is spent for cooling than consumed by the computing tasks inside that hotspot. By avoiding the chances of hotspots, the extra burden over cooling infrastructure can be avoided and power can be saved.

There are multiple factors which may combine to provide suitable condition for a hotspot. Among these factors is the physical phenomenon of cold air getting warmer as it reaches the inlet of the servers mounted near the top of racks. Furthermore, some systems such as the legacy servers are less power efficient and thus dissipate more heat. It depends upon the processor model being installed in the server. The processor is the most power consuming and thus the most heat dissipating hardware equipment on the motherboard (EPA, 2007). Legacy processor architecture lacks the adaptive power usage capability and consumes more power compared to modern processor (Huck, 2011) and therefore dissipate more heat (Manuel Masiero, 2012). Servers which consume comparatively more power when idle are more prone to give rise to hotspots than others. A server is considered power efficient if it consumes comparatively less power when idle and provides more computing power per watt in terms of MHz per watt when active.

The chances of hotspot can be foreseen by analyzing the heat dissipation of different servers at various locations inside a data center with respect to inlet air temperature. This is due to the fact that some servers may dissipate more heat at higher inlet temperature while some servers may not be that sensitive, owing to the hardware architecture. Based upon this fact, if the physical location of each server is determined according to the inlet temperature sensitivity, the peak outlet temperature of the servers and the chances of hotspots can be reduced. For the servers that are already mounted in racks, the inlet temperature sensitivity analysis can help in rearranging the locations of a set of servers. Hotspot avoidance based relocation of data center servers can be a part of capacity planning or it can be done in parallel with traditional cooling mechanism optimization based techniques (Lee *et al.*, 2012). The server relocation technique proposed in this paper is a novel approach for minimizing the chances of hotspots and greening the data centers.

The rest of the paper is arranged such that section 2 describes the related literature review and section 3 explains the energy model preliminaries. Section 4 refers to the server relocation algorithm which is tested on experimental setup, explained in section 5. A comprehensive discussion is provided in section 6 to analyze the experimental results and the application of the server relocation algorithm. The paper ends with recommendations for server relocation in section 6.1 and a conclusion in section 7.

2 Related work

A power profiling based thermal map prediction and equipment relocation technique was reported by (Jonas *et al.*, 2010). Thermal map prediction was based on power profiles of the server chassis. On the basis of the fact that every chassis makes contribution to the heat recirculation of all the chassis in the data center, an equipment relocation algorithm was proposed. However, it is practically complex to access the heat recirculation contribution coefficient for each of the hundreds of chassis in a data center. These techniques should only focus on the hotspot servers to decrease the complexity of implementation. If the servers with high electricity consumption or the servers having high utilization rate are placed at top of the racks where the inlet temperature is high, then doing so will increase the outlet temperatures of these servers instead of decreasing.

If a power saving technique such as diskless booting is used as proposed by (Che-Yuan *et al.*, 2010), then the servers will dissipate even less heat if they are located in a way that the inlet temperature has minimum effect on increasing the outlet temperatures of the servers. If the power consumption profiles of server are created so that the least power is used to execute a given computing load and to ensure performance and profit as in (Kusic *et al.*, 2009), then the scheduling algorithm can save more power if the hotspots are avoided.

Instead of using a neural network to predict the outlet temperature, the thermal profiles can be utilized to predict the thermal map and chance of hotspots (Jonas *et al.*, 2007; Jonas *et al.*, 2010). Inlet temperature variation may lead to hotspot and cause an additional burden to the cooling mechanism. Data center energy efficiency and power consumption based scheduling techniques can perform better if the computational workload is distributed among servers on the basis of comparatively lower inlet temperature preference (Tang *et al.*, 2007; Mukherjee *et al.*, 2009; Ahuja, 2012). Similarly the reduction in recirculation of heat is more effective if the servers are arranged according to their sensitivity to inlet temperature hike (Tang *et al.*, 2007).

The research aiming to increase the thermostat setting (Banerjee *et al.*, 2010; Banerjee *et al.*, 2011) for cold air in data center or to model the thermal map (Qinghui *et al.*, 2006; Ahuja *et al.*, 2011) should consider the optimization of server locations as a prerequisite to implementation. This is also applicable to recent ASHRAE (ASHRAE-TC-9.9, 2011) standards for enhanced inlet temperatures. The coefficients of heat recirculation and heat extraction for the data center servers (Qinghui *et al.*, 2006) are sensitive to the inlet temperature increment and the value of coefficients should not be affected by this phenomenon. If servers are utilized to the maximum level through backfilling (Lizhe *et al.*, 2009; Wang *et al.*, 2009), then the chances of hotspots are increased with the increase in inlet temperature. Therefore the inlet temperature should be considered before backfilling or the servers should be relocated accordingly and then backfilled to avoid hotspots. Similarly, the server consolidation techniques for minimizing the number of active servers should only choose those servers which will not cause hotspots. This is because the consolidated servers will be at their peak utilization all the time (Corradi *et al.*, 2011).

Task-temperature profiles used for thermal-aware workload scheduling should consider the effect of inlet temperature sensitivity of the physical servers upon the scheduling outcome in terms of the thermal map to be unexpected (Wang *et al.*, 2012). The thermal profiling based techniques such as (Rodero *et al.*, 2012) and (Ivan Rodero *et al.*, 2010) cannot estimate and create the generic profiles of all the homogenous servers which are located at different inlet air temperature across data center. Hence there is a gap in research related to the thermal-aware arrangement of data center server. This paper presents a thermal-aware server location evaluation and relocation of virtualized data center servers to optimum locations. This results in prevention of possible hotspots and cooling energy saving as well as the increased effectiveness of thermal-aware scheduling techniques.

Cooling-aware workload placement with performance constraints was proposed by (SansotteraandCremonesi, 2011) in which the rise in inlet temperature is due to heat recirculation. The heat recirculation was considered to be due to the air flow. The temperature of hot air from each server was declared to be due to power consumption according to computational workload on that server. Various test case scenarios were analyzed by CFD simulations with different power consumption levels for the servers in order to profile each server for the heat recirculation. This approach is based upon the prior work of (Qinghui *et al.*, 2006). These profiles were used to evaluate the highest possible thermostat setting, the lowest possible heat recirculation and maximize the performance. This approach leads to the utilization of each server according to the thermal-profile. The simulated scenario of the data center has two CRAC units at two opposite boundaries of the data center hall. One of these CRAC units was turned off so that hot air would be removed less efficiently from that region and heat recirculation may occur. In such a case, the servers which have a high heat recirculation impact are always underutilized. The servers consume up to 60% of peak power in the idle state as shown by our experiments. Therefore it is not energy efficient to keep some servers idle or underutilized. Instead, we propose to identify the servers which are affected by heat recirculation and identify the outlet temperature at various utilization levels. Then, such servers can be relocated at other locations inside the data center so that these servers can be utilized to maximum with comparatively lower outlet temperature at the new location.

In pioneer work, (Qinghui *et al.*, 2006) proposed to create the heat recirculation profiles and heat-exit profiles of the data center servers by using various power consumption levels in CFD simulations. These profiles can be used to predict the thermal map of the data center, given a power distribution vector and heat recirculation coefficient matrix. This is a faster method for thermal prediction. However, the CFD simulations consume great time in hours multiples of number ten. Also, heterogeneous servers do not necessarily consume the same amount of power at the same level of CPU utilization and therefore do not have the same outlet temperatures despite the same inlet temperature. This makes the CFD based profiling approach prone to hardware related limitations that can only be verified through experiments upon real hardware as we show in this paper.

3 Data center energy modeling preliminaries

By the law of energy conservation, the watts of electrical power consumed are converted into equivalent joules of thermal energy (GmbH). From now on the words "power", "electricity" and "energy" are used interchangeably (where energy is consumed per unit of time). If $E^i_{computing}$ is the electricity consumed by a data center server *i* then this energy is converted to E^i_{joules} as shown in Eq. (1).

$$E^i_{computing} = E^i_{joules} \tag{1}$$

As explained in (Moore *et al.*, 2005), power consumed by a water chilled computer room air conditioning (CRAC) units at HP labs is calculated with reference to the cold air set temperature and is called the coefficient of performance (COP). The COP is the amount of work done *w* to remove heat *Q* as shown in Eq. (2).

$$COP=Q/w. \tag{2}$$

The COP has a numeric value which increases with the increase in supplied cold air temperature. The electrical energy $E_{cooling}$ consumed to remove the heat dissipated by a server *i* by supplying the cold air at a set temperature $T^i_{received}$ can be written as in Eq.(3). The Eq. (3) however differs from (Moore *et al.*, 2005) as it considers the inlet air temperature that each server is receiving.

$$E^i_{computing} = E^i_{joules}/COP(T^i_{received}). \tag{3}$$

The cold air gets hot when it travels towards servers from the perforated tiles of a hollow floor and due to heat recirculation. The hike in inlet air temperature has a direct impact on outlet air temperature for each server. The servers near the top of each rack are the victims of this phenomenon. These servers will dissipate more heat because the inlet air temperature increases despite the fact that they might not be utilized at full. So the servers at the top of the racks put more burden on the cooling system than the servers near the floor, because of the rise in inlet air temperature. The COP curve (Moore *et al.*, 2005) is unable to give a solution to this.

Therefore if the total electricity consumption E^i_{Total} for running a server *i* can be written as in Eq. (4),

$$E^i_{Total} = E^i_{computing} + E^i_{cooling}, \tag{4}$$

Using Eq. (3)

$$E^i_{Total} = E^i_{computing} + \{E^i_{joules}/COP(T^i_{received})\}, \tag{5}$$

Using Eq. (1)

$$E^i_{Total} = E^i_{computing} + \{E^i_{computing}/COP(T^i_{received})\}. \tag{6}$$

The total energy consumption of data center can be written as in Eq. (7)

$$E_{Total} = \sum_{i=1}^{n} E^i_{Total} = \sum_{i=1}^{n}\left(E^i_{computing} + \frac{E^i_{computing}}{COP(T^i_{received})}\right), \tag{7}$$

or

$$E_{Total} = \sum_{i=1}^{n} E^i_{computing}\left(1+\frac{1}{COP(T^i_{received})}\right). \tag{8}$$

The total electrical energy consumed by a data center as shown in Eq. (8) contains the electrical energy consumed by physical servers and the cooling system. Thus with the knowledge of electricity consumption of the servers, the data center's cooling energy and therefore the total energy consumption can be calculated. This paper proposes to calculate the cooling energy consumption for each server based upon the inlet air temperature at that server. This means that the COP value should not be taken at the set inlet air temperature T_{set} of CRAC. A useful fact is that the COP value rises with the rise in inlet air temperature. So a server that is receiving the cold air at a higher temperature will be responsible for a smaller share in total cooling energy consumption according to Eq. (8). On the other hand, the servers having high temperature of inlet air $T_{received}$ will have a corresponding increase in the outlet air temperature as shown in Eq. (9).

$$\Delta T^i = T^i_{received} - T_{set}, \tag{9}$$

where ΔT^i is the increase in inlet temperature of server *i* and causes the equivalent increase in outlet temperature of the server. The original outlet temperature can be given by the following

$$T^i_{outlet} = T^i_{outlet(increased)} - \Delta T^i. \tag{10}$$

The increased outlet temperature of a server due to increase in inlet temperature not only puts extra burden on the cooling mechanism but also may form hotspots. The formal effect is independent of workload on the server while the latter occurs when the server is executing the workload. The servers with higher than set temperature of inlet air $T^i_{received} > T_{set}$ means that the cooling energy is wasted for any server *i* as shown in Eq. (11).

$$\Delta E^i_{T\_inlet} = E_{T\_set} - E^i_{T\_received}, \tag{11}$$

where E_{T_set} is a subset of electricity used to provide cold air to server *i* at temperature T_{set} but it should have been $E^i_{T\_received}$ instead. This is because $T^i_{received} > T_{set}$ and therefore $E_{T\_set} > E^i_{T\_received}$. So $\Delta E^i_{T\_inlet}$ is the energy wasted for server *i*. As a result the outlet temperature rises by ΔT^i degrees as per Eq. (9). This causes an equivalent energy to be wasted to cool the outlet air of server *i* that is extra hot by ΔT^i degrees. Therefore the total cooling energy wasted is the sum of cooling energy wasted and the extra cooling energy spent for all servers and can be given by Eq. (12):

$$\begin{aligned} E_{cooling\_wasted} &= \sum_{i=1}^{n} (\Delta E^i_{T\_inlet} + \Delta E^i_{T\_inlet}) \\ &= \sum_{i=1}^{n} 2\Delta E^i_T. \end{aligned} \tag{12}$$

The value of $\Delta E^i_{T\_inlet}$ will be equal to or more than zero depending upon the position of server with respect to floor. In this paper, we propose to minimize the energy wastage on cooling as given by Eq. (12). The maximum allowed inlet temperature can be represented by $T_{\max}$ beyond which either the hotspot can occur or the server hardware may fail.

We define a problem statement for equipment relocation as:

If there exists $server^i$ **such that**
$T^i_{received} > T_{set}$
Find $server^j$ **where**
$T^j_{received} < T^i_{received}$ **And** $T^j_{outlet} < T^i_{outlet}$
And $T^i_{outlet} < T_{\max}$ **And** $T^j_{outlet} < T_{\max}$
Subject to post relocation conditions given by:
$T^{i(relocated)}_{outlet} < T^i_{outlet}$ **And** $T^j_{outlet(increased)} < T^i_{outle}$
And $(T^j_{received} - T_{set}) < (T^i_{received} - T_{set})$
And $E_{cooling\_wasted}$ **is minimized**

The energy wasted in cooling as shown in Eq. (11), can be minimized by equipment relocation. Since this energy wastage is curable and therefore should not be included in calculating the total energy consumption. So the Eq. (8) can be generalized to

$$E_{Total} = \sum_{i=1}^{n} \left(E^i_{computing} \left(1 + \frac{1}{COP(T_{set})} \right) - E_{cooling\_wasted} \right). \tag{13}$$

Using Eq. (6) and Eq. (12), the value of $E_{cooling\_wasted}$ can be solved. The increase in cooling energy wastage results in a rise in data center PUE. The calculation of $E_{cooling\_wasted}$ can be performed through the thermodynamics model given by (Qinghui *et al.*, 2006) which requires the data on the blow rate of the server fans. The servers used for demonstration (as shown in Table 1 in this paper have dynamic fan rates and thus the calculation of the $E_{cooling\_wasted}$ becomes complicated. Instead, the cooling cost was calculated indirectly through the approach proposed by (Moore *et al.*, 2005). According to this, the cooling cost is calculated with reference to the COP of the set temperature of the CRAC unit. We have extended this model for the calculation of $E_{cooling\_wasted}$ before applying the relocation algorithm. The energy wasted is calculated as a difference between the cooling energy for the supplied air temperature and the temperature of the cold air received by the servers. This is demonstrated in Eq. (14).

$$E_{cooling\_wasted} = \sum_{i=1}^{m} 2\Delta E_T^i = \sum_{i=1}^{m} 2*\left(\frac{E_{computing}^i}{COP(T_{set})} - \frac{E_{computing}^i}{COP(T_{received}^i)}\right). \quad (14)$$

This paper proposes lowering the cooling energy wastage by adjusting the location of the servers. While it may not be possible to totally eliminate $E_{cooling\_wasted}$ a possibility is to normalize the cooling energy wastage due to increase in inlet temperature by lowering the average outlet temperature of the affected server/s through relocation.

Considering the same volume of air at temperature T_1 degrees is heated to T_2 degrees, then the heat at temperature T_2 is greater than at T_1 (BBC, 2014). Applying the same concept on server outlets; if the temperature of the server outlet is lowered, then this signifies the lowering of heat. As from Eq. (10), if the server is relocated to a location with comparatively lower inlet temperature, then the amount of heat dissipated is lower because the temperature of the outlet is comparatively lower at the new location. Thus, the cooling load is lowered. For the server which is relocated to the region of high inlet temperature as a location exchange, if the outlet temperature is lower than that of the previous server at the same location, the overall cooling load of both servers is decreased. The more the homogeneous and comparatively lower are the temperatures of the relocated servers, the lower is the cooling load.

From Eq. (10), it can be inferred that the outlet temperature depends upon inlet temperature and the server utilization level. If the server utilization remains the same, a change in inlet temperature has a direct impact upon outlet temperature. This allows prediction of the outlet temperature of server *i* at current inlet temperature $T_{received}^i$ with respect to the inlet temperature of server *j*. Thus

$$T^i_{predicted\_outlet} = (T^i_{outlet} - T^i_{received}) + T^j_{received}. \quad (15)$$

The predicted outlet temperature of the servers *i* and *j* can be used to evaluate the current location of each server for the possibility of hotspots. In this paper, Eq. (15) is used to predict an array of outlet temperature values for any server. The next section presents the experimental setup used to solve the relocation problem.

4 Server Relocation Algorithm

This section presents the server relocation algorithm based upon the analysis and comparison of various variables related to performance, power and temperature. These variables are represented by vectors as explained in the previous section. Before proceding, it should be noted that the arithmatic and logical operations performed between two vectors are implemented on the corresponding elements of vectors in time sine the identical experiments were run on all servers. There can be a list of heterogeneous servers with the experiments performed and data gathered on atleast one member of each heterogeneous server type before relocation. The relocation algorithm can be applied on two servers at a time. Therefore for the sake of simplicity, two heteregenous server types are considered in the algorithm. These are named as *server type A* and *server type B* as shown in Table 1. One member from each type of servers is chosen for the implementation. The arithmetic and logical operations performed between a vector and a scalar are performed on each element of vector with the same value of scalar.

```
Server_Relocation ($\boldsymbol{T}^A_{idle\_inlet}$, $\boldsymbol{T}^B_{idle\_inlet}$, $\boldsymbol{T}^A_{inlet}$, $\boldsymbol{T}^B_{inlet}$, $\boldsymbol{T}^A_{outlet}$, $\boldsymbol{T}^B_{outlet}$, $T_{\max}$)
{
    If ($\boldsymbol{T}^A_{idle\_inlet} < \boldsymbol{T}^B_{idle\_inlet}$ And ($\boldsymbol{T}^A_{idle\_inlet} < T_{\max}$ And $\boldsymbol{T}^B_{idle\_inlet} < T_{\max}$))
    {
        $\Delta\boldsymbol{T}_{inlet} = \boldsymbol{T}^B_{inlet} - \boldsymbol{T}^A_{inlet}$
        $\Delta\boldsymbol{T}_{outlet} = \boldsymbol{T}^B_{outlet} - \boldsymbol{T}^A_{outlet}$
        if ($\Delta\boldsymbol{T}_{inlet} > 0$ And $\Delta\boldsymbol{T}_{outlet} > 0$)
        {
            if ($\Delta\boldsymbol{T}_{outlet} \geq \Delta\boldsymbol{T}_{inlet}$)
            {
                Calculate $\boldsymbol{T}^B_{predicted\_outlet}$ through Eq.(15)
                Calculate $\boldsymbol{T}^A_{predicted\_outlet}$ through Eq.(15)
                If ($\boldsymbol{T}^A_{predicted\_outlet} \leq \boldsymbol{T}^B_{outlet}$ And $\boldsymbol{T}^A_{predicted\_outlet} \leq \boldsymbol{T}^B_{outlet}$)
                {
                    switch locations of server type A and server type B
                }
```

```
17              }
18            }
19        }
20      }
```

The proposed algorithm requires the idle state inlet temperatures and other parameters of two servers at each run. The idle state inlet temperatures are required to identify the difference in inlet temperatures and that the inlet temperature is less than the vendor specified maximum temperature as shown in listing (3). It is supposed that $T_{\max}$ is same for all servers. Otherwise listing (3) can have different values for $T_{\max}$. The experiments performed on the pair of serves generate the data such as $\boldsymbol{T}^{A}_{inlet}$, $\boldsymbol{T}^{B}_{inlet}$, $\boldsymbol{T}^{A}_{outlet}$ and $\boldsymbol{T}^{B}_{outlet}$. The algorithm proceeds further if server type A is located at an inlet temperature lower than server B. In listing (7, 9) the checks are performed to confirm that the differences in inlet and outlet temperatures of the two servers are available and the outlet temperature difference is larger than the inlet temperature difference. This provides an opportunity for predicting the outlet temperatures in listing (11–12). If the predicted temperaure of server type A after relocation is lower than the outlet temperature of server type Bbefore relocation and the predicted temperature of server type B after relocation is lower than the outlet temperature before relocation then the algorithm suggests switching locations of the servers.

In the next section, we explain the algorithm with respect to experiment sets in Fig. 2 where graphs shown are based upon the real data gathered from experiments when the servers were placed at initial locations. The data is from three sources which are: thermal sensors, smart power meters and the virualized hosts and is aggregated per host and per minute to match the time and hosts.

5 Experimental Setup

The proposed approach was tested over a set of heterogeneous servers, running VMware ESXi 5.0 (VMware, 2009) hypervisor. We used virtualized servers (hosts) as the hypervisor can give the detailed performance data and the frequency of server processor can be manipulated at run time. This helps in simulation for various processor frequencies to simulate the routine at which servers are actually used in data center.

Servers were grouped according to their processors models; Intel(R) Xeon(R) CPU E5430 2.66GHz and Intel(R) Xeon(R) CPU E5320 1.86 GHz respectively. The server groups were named *Server Type A* and *Server Type B* as shown in Table 1. The members of each server group are homogenous. For implementation, two servers; one of type A and other of type B were used.

Table 1 Server types

Server Type	Processor
A	Intel(R) Xeon(R) CPU E5430 2.66GHz
B	Intel(R) Xeon(R) CPU E5320 1.86 GHz

To monitor the inlet and outlet air temperatures, external USB thermal sensors were used. The power consumption of each host was measured by USB smart power meters. Each server has up to 8 virtual machines (VMs). Microsoft C# script was used as the workload booster to manipulate the VM operations. Each VM is running a CPU intensive benchmark *Prime95* (“Great Internet Mersenne Prime Search (GIMPS),” 2012) and is kept in suspended state. Each VM has a single virtual CPU. Server type A was run idle for about 10 hours to prove the correlation between inlet and outlet temperatures.

Fig. 1 shows that the close correlation occurs between the inlet temperature and outlet temperature of the prototype servers in idle state. Experimental results presented in a latter section show that this relationship holds when the servers is active and this is a basic matrix of evaluating the post relocation outlet temperatures from the set of servers involved. We performed three sets of experiments involving one server from group A and another from group B as shown in Table 2 at various CPU frequencies for server group A and B. Each experiment set contains at least two servers. Since the servers are heterogeneous and the difference between the processor frequencies is 0.8 GHz. Dynamic frequency scaling was used to vary the maximum flips of the servers according to Table 2. The experiment sets 2 and 3 have the servers running at same processor frequency and can approximately represent the scenarios when the servers are running underutilized.

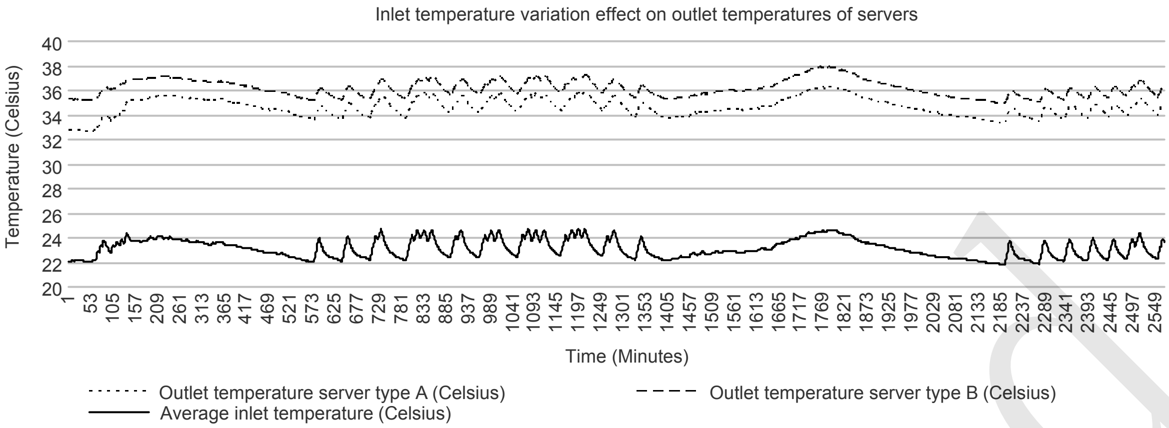

Fig. 1 The correlation between inlet temperature and outlet temperatures of type A and type B servers

While in set 1, both the servers undergo maximum utilization.

Table 2 The sets of experiments performed. Each experiment set involves both servers. Server type A has speedier processor than server type B.

Experiment set	Server type a processor frequency	Server type b processor frequency
1	2.66 GHz	1.86GHz
2	1.86 GHz	1.86GHz
3	1.0 GHz	1.0 GHz

All the experiment sets take 3 minutes idle time to start and then utilize the virtualized hosts (according to the frequency limit of experiment sets) for 30 minutes and then bring the host to idle state to cool down to idle state temperature for 20 minutes. Altogether, each experiment takes approximately 55 minutes. The set temperature T_{set} was at 21 Celsius. The initial location of the servers was such that server type A was placed in a colder area and server type B was located in a hotter area. Table 3 shows the initial conditions of the servers. On average, server type A uses less power when in idle state than server type B and this causes the average outlet temperature to be higher than the server type A in idle state as shown in Table 3. But server type A is receiving the inlet temperature at T_{set} which is lower than the inlet temoerature of server type B. This can be another reason of comparatively lower outlet temperature of server type A. The COP for server type A is also lower than server type B according to inlet temperature receieved.

This lead to a hypothesis that the maximum temperature from hot air outlet of server type A will be lower than the maximum temperature from hot air outlet of server type B if maximum power consumed by server type A is equal to the maximum power consumed by server type B provided that server type A has a lower inlet temperature than server B.

Table 3 The idle state statistics of both servers. Server type B uses more electricity in idle state

Server type	Average inlet temperature (Celsius)	COP ($T^{i}_{received}$)	Average idle state power consumption (watts)	Average idle state outlet temperature (Celsius)
A	21.2	3.5	205	31.8
B	22.7	4.0	232	35.4

If both servers consume equal electricity while running identical workloads, then if the outlet temperature of server type B is greater than server type A then this indicates the impact of inlet air temperature. If server type B has a less powerful processor than server type A, then it will be giving less MHz per watt of power consumption than server type A. If the processor of server type A has a higher maximum frequency and consumes less power in idle state and equal power at any level of processor utilization as compared to server B(indicated by the outlet air temperature), then it will be worth predicting the outlet temperature of both servers after relocation on the basis of inlet temperature difference.

In idle state of servers, suppose that vector $\boldsymbol{T}^{A}{}_{idle\_inlet}$ and vector $\boldsymbol{T}^{B}{}_{idle\_inlet}$ represent the inlet air time lapsed temperatures' series of server type A and Server type B respectively. Assume that $\boldsymbol{T}^{A}{}_{idle\_inlet}$

and $\boldsymbol{T}^B_{idle\_inlet}$ cover a reasonable time to make inference. If $\boldsymbol{P}^A_{idle}$ and $\boldsymbol{P}^B_{idle}$ are the idle power consumption vectors of server type A and server type B respectively. During the experiments mentioned in Table 2, the outlet temperatures of the servers were saved in vectors $\boldsymbol{T}^A_{outlet}$ and $\boldsymbol{T}^B_{outlet}$ for server types A and B respectively. The inlet temperatures of the servers A and B were recorded in vectors $\boldsymbol{T}^A_{inlet}$ and $\boldsymbol{T}^B_{inlet}$ respectively.

Given that $\boldsymbol{T}^A_{idle\_inlet}<\boldsymbol{T}^B_{idle\_inlet}$ then $\boldsymbol{T}^A_{max\_outlet}<\boldsymbol{T}^B_{max\_outlet}$ provided that $\boldsymbol{P}^A_{\max}\le\boldsymbol{P}^B_{\max}$. Where $\boldsymbol{T}^A_{max\_outlet}$ is the maximum outlet temperature vector from server type A when it consumes maximum power $\boldsymbol{P}^A_{\max}$ and $\boldsymbol{T}^B_{max\_outlet}$ is the maximum outlet temperature vector of server type B when it consumes maximum power $\boldsymbol{P}^B_{\max}$. If this hypothesis is proved through experiments given in Table 2, then the next step will lead to an algorithm for equipment relocation.In the next section, this hypothesis is tested and furher analysis is made to relocate the servers with the objective of lowering the cooling load and to avoid hotspots.

6 Experimental results and discussion

In this section, the experimental results are presented and discussed with respect to the server relocation algorithm presented in the previous section. Listing-1 of the algorithm can get the parameters from Figs. 2.1 and 2.2 inwhich the servers under go the experiment of maximum workload and CPU utilization. As per Figs. 2.1–2.3, listing-3 of the algorithm is true for both hosts as the idle state inlet temperature and the maximum outlet temperature of server type A is always less than server type B which indicates that if the difference in outlet temperature is dependent upon the difference in inlet temperatures, then after swiching places, if the same experiment is performed, then server type A will have leser outlet temperature than server type B at same location. It makes the server type A a good candidate for switching location wih server B.

In order to verify that the inlet temperature and the outlet temperatures of both servers throughout the experiment remained such that the server type B always had the higher inlet temperature and higher outlet temperature than server type A, the operations

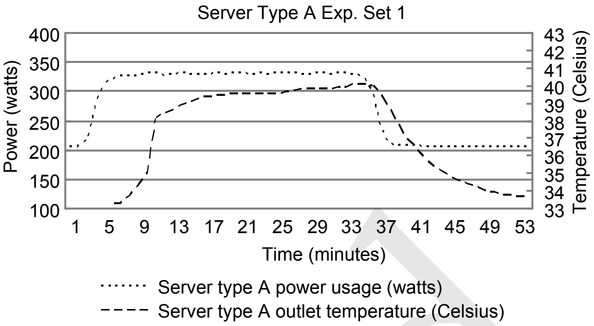

Fig. 2.1 Server type A at maximum power usage and maximum outlet temperature

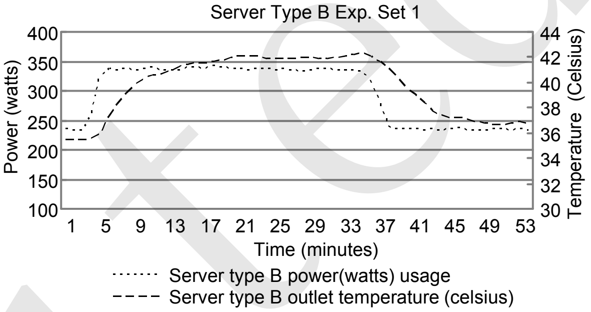

Fig. 2.2 Server type B at maximum power usage and maximum outlet temperature

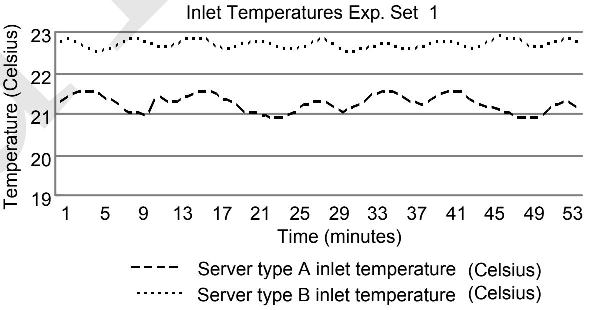

Fig. 2.3 Inlet temperatures of Server type A and Server type B when Server type B is receiving hotter air at inlet

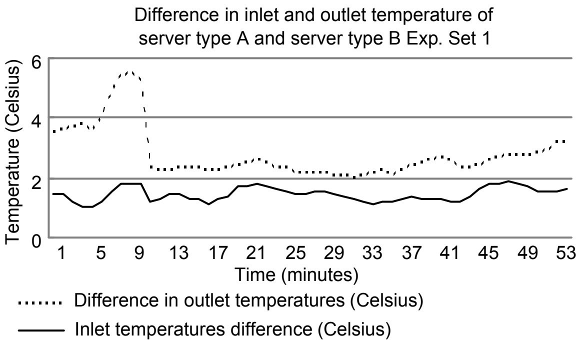

Fig. 2.4 The difference between inlet temperatures is always higher than the difference between outlet temperatures for Server type A and Server type B at initial locations

of listings-5-6 are to be performed. If the difference between the inlet temperatures $\Delta \boldsymbol{T}_{inlet}$ remains above zero (listing-7) then it means that the outlet temperatures of both servers will be such that the server type A will have lower outlet temperature than server B. As shown in Fig. 3.4, the graph of outlet temperature difference $\Delta \boldsymbol{T}_{outlet}$ remains around value 2 on y-axis. The distance between $\Delta \boldsymbol{T}_{outlet}$ and $\Delta \boldsymbol{T}_{inlet}$ graphs shows how much more heat is dissipated from server type B than the inlet temperatures difference. This distance is quite significant in Fig. 2.13 when both servers run exp. set 2 & 3. We present the combined results of exp. set 2 & 3 in Figs. 2.10–2.15. As per Eq. (1), all the electricity is to be converted into heat. Therefore, unless the server type A consumes more electricity than server B, the outlet temperature of server type A will remain less than server type B and the logical comparison of listing-7 will be true. The power consumptions of both servers shown in Figs. 2.1–2.2 show that the maximum power consumption of server type A is always less than or equal to the power consumption of server type B throughout the experiment. Hence the hypothesis presented earlier is proved. This is shown in Fig. 2.4. The big hump in Fig. 2.4 of $\Delta \boldsymbol{T}_{outlet}$ graph is the sudden rise in outlet temperature of server B, while the server type A took a while to get heated. This may be due to the fact that server type B consumes more energy in idle state than server type A and when the exp. set is conducted over server B, the rate of rise in electriciy consumption of server type B rises more sharply than server A during a short interval.

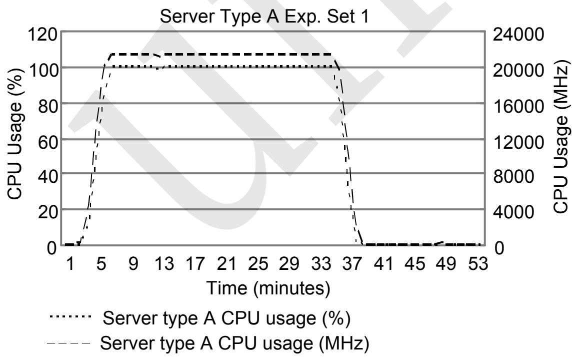

Fig. 2.5 The maximum utilization of Server type A

CPU utilization and effective Megahertz (MHz) of both servers are shown in Figs. 2.5–2.6. Both servers under go maximum utilization of CPU, although they differ in maximum MHz. Before finalizing the decission to switch locations of both servers, the temperature predicion should be made. This is to fore see the effect of relocation (listings-11-12) and shown in Figs. 2.7–2.9. The inlet temperature difference $\Delta \boldsymbol{T}_{inlet}$ is added to the outlet of server type A to raise it and the same is subtracted from server type B outlet temperaure to lower it.

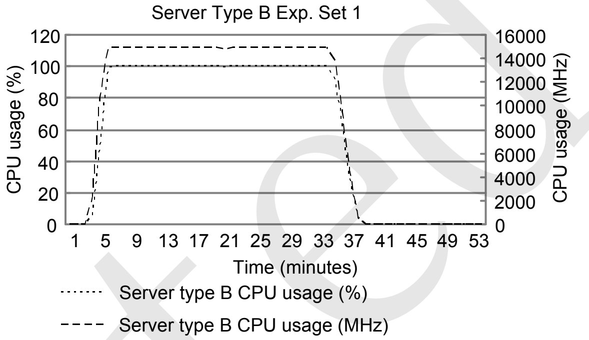

Fig. 2.6 Server type B has a lower maximum frequency than Server B

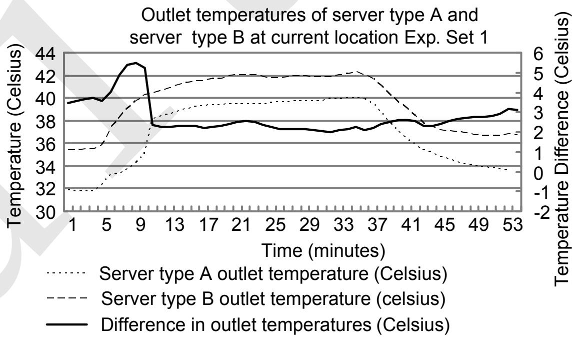

Fig. 2.7 The hump in outlet temperature difference curve is due to a sudden rise in outlet temperature of server B

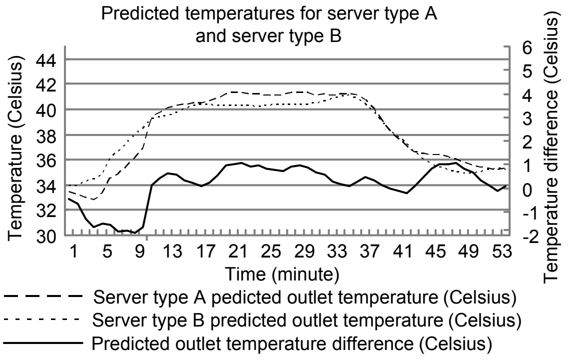

Fig. 2.8 Predicted temperature of server type A and server type B after relocation on the basis of inlet temperatures

As shown in Fig. 2.9, the predicted temperature of server type A represented by $\boldsymbol{T}^{A}_{predicted\_outlet}$ is less than the outlet temperature of server type B represented as $\boldsymbol{T}^{B}_{outlet}$ and the predicted outlet temperature of server B: $\boldsymbol{T}^{B}_{predicted\_outlet}$ is also lower than $\boldsymbol{T}^{B}_{outlet}$. This means that if the same experiment is repeated after switching the locations of both servers, then the server type B will not only have a lower outlet temperature than the previous location, but the server type A will also dissipate less heat at the new location than server type B at the old location.

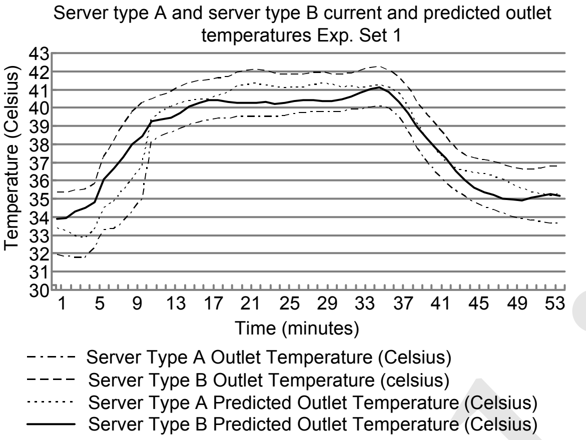

Fig. 2.9 The predicted temperatures will lower the difference between peak temperatures of both servers

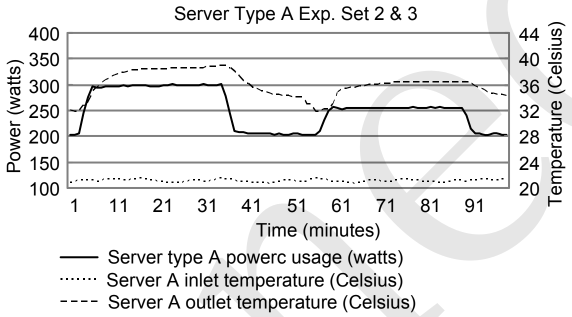

Fig. 2.10 Power consumption and oulet temperature of Server-A running at lower frequency to match the processor of Server B

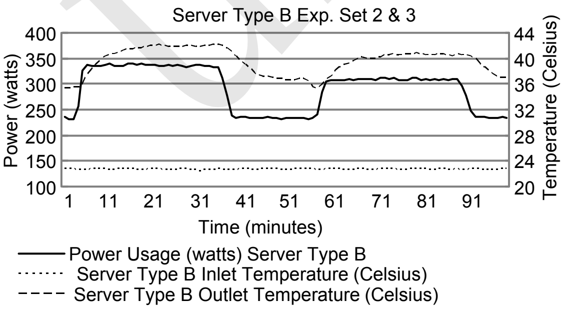

Fig. 2.11 Power consumption and oulet temperature of Server-B running at frequencies equal to Server type A. The temperature is higher than Server type A

The logical comparisons of listing-13 are the post relocation conditions that were presented earlier in the problem statement and they gurantee that the relocation operation will result in hotspot avoidance and overall reduction in cooling load with homogenous outlet temperatures of both servers. A significant differnce between $\Delta\boldsymbol{T}_{inlet}$ and $\Delta\boldsymbol{T}_{outlet}$ shown in Fig. 2.13 which shows a major imbalance in heat dissipation when the servers are underutilized. Server type A is being under utilized in exp. 2 & 3, but server type B is fully utilized in exp. set 2 and under utilized in exp. set 3. But server type B always consumes more energy than server type A and provides less MHz per watt than server type A. Server type B dissipates more heat even when both servers run at almost similar CPU frequencies in exp. set 2& 3.

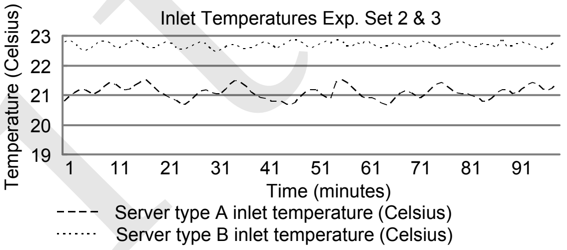

Fig. 2.12 Inlet temperatures of Server type A and Server type B when Server type B is receiving hotter air at inlet

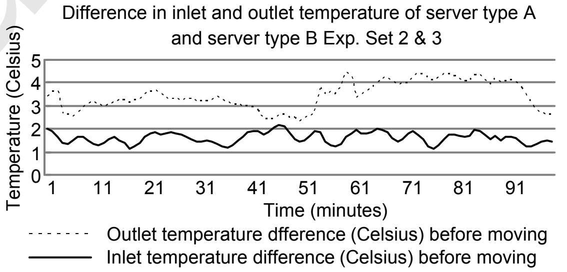

Fig. 2.13 The difference between air outlets and the air inlets of Server type A and Server B. The formal difference is much higher than the latter. But the relocatin algorithm does not use this

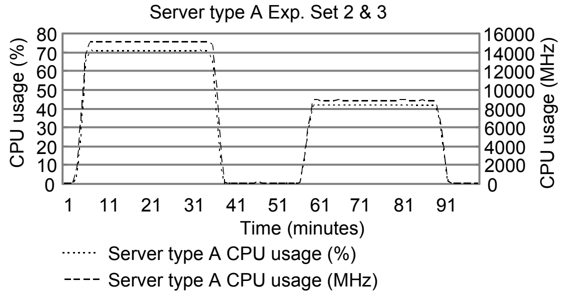

Fig. 2.14 Server type A was run underutilized to match the processor frequency of server B

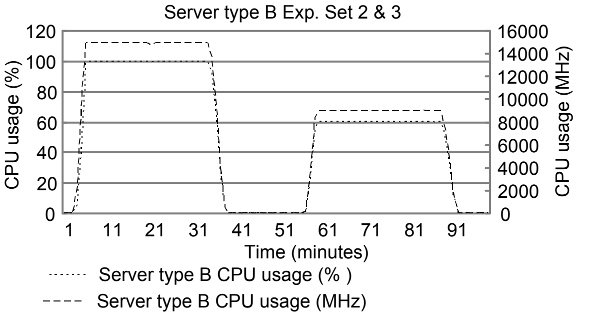

Fig. 2.15 Server type B running at its full processor in Exp. Set 2 and at 60% of its maximum frequency

Now we move on to the verification of post relocation considerations mentioned earlier in problem statement. The same sets of experimens were performed over server type A and server type B after switching their locaions. The results are shown in Figs. 3.x where Figs. 3.1–3.2 indicae that server type B shows a reduction in outlet temperture whereas server type A outlet temperature is increased as compared to Fig.2.1–2.2 with the increase in inlet temperature. But the power consumption of both servers follow the same trend as before relocation (Figs. 2.1–2.2) when exp. set 1–3 are repeated and so did the inlet air temperaures (Figs. 2.3, 3.4 and 3.9). The hump of Fig. 2.4 for $\Delta \boldsymbol{T}_{outlet}$ is flatened in Fig. 3.3 showing a positive change in difference between outlet temperatures. This shows that although the power consumptioin of server type B shoots up in the start of exp. set just as in Fig. 2.2, but the rise in outlet temperature of server type B in Fig. 3.2 is balanced by the higher rate of rise in oulet temperature of server type A in Fig. 3.1. This hump was responsible for an error in prediction of Fig. 2.8 for a short interval of 4 minutes.

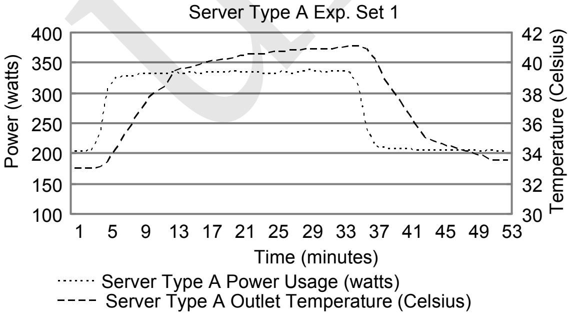

Fig. 3.1 Server type A shows an increase in outlet temperature. But the power consumption is same as before moving.

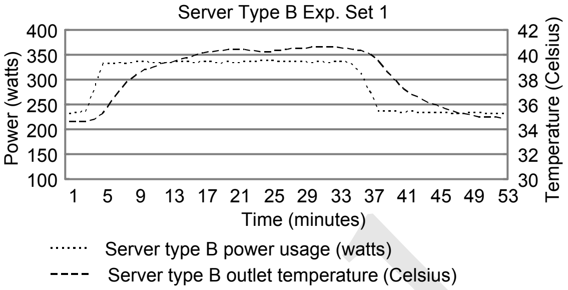

Fig. 3.2 Server type B shows an decrease in outlet temperature. But the power consumption is same as before moving

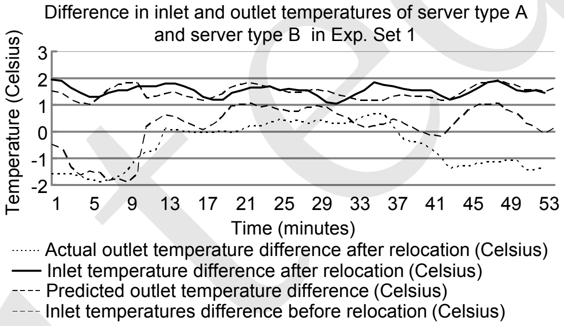

Fig. 3.3 The predicted difference in outlet temperatures was more accurate when the servers are running at maximum utilization

Figs. 3.3 and 3.10 show that the predicted $\Delta \boldsymbol{T}_{outlet}$ curve follows closely to the curve of actual run. As shown in Figs. 3.5 and 3.11, the predicted temperatures' curves of $\boldsymbol{T}^{A}_{predicted\_outlet}$ and $\boldsymbol{T}^{B}_{predicted\_outlet}$ follow closely with the actual outlet temperatures' curves of $\boldsymbol{T}^{A}_{outlet}$ and $\boldsymbol{T}^{B}_{outlet}$. Since the predicted outlet air temperature of server type A was less than that of server type B and that was a reason to relocate it, the fig. Fig.3.5 shows that the curve of $\boldsymbol{T}^{B}_{predicted\_outlet}$ is more accurate than of $\boldsymbol{T}^{A}_{predicted\_outlet}$. The reason is that the $\boldsymbol{T}^{A}_{predicted\_outlet}$ was calculated, based upon $\Delta \boldsymbol{T}_{outlet}$ which depended upon the curve of $\boldsymbol{T}^{B}_{outlet}$ at the previous location. Therefore according to listing-13 of the algorithm, the servers could be relocated even if the $\boldsymbol{T}^{A}_{predicted\_outlet}$ be equal to $\boldsymbol{T}^{B}_{outlet}$ before relocation. This is proved by Figs. 3.11 and 3.12.

The results of exp. sets 2 & 3 in Figs. 3.11 and 3.12 prove the post relocation scenario. The significant difference between the curves of $\Delta \boldsymbol{T}_{outlet}$ in Fig. 2.13 and of exp. set 3 in Fig. 3.10 is due to the fact that server type B dissipates more heat at low CPU utilization than server type A even when $\boldsymbol{T}^{A}_{inlet} \geq \boldsymbol{T}^{B}_{inlet}$. The averaged results of the experiments before and after relocation are summarized in Tables 4–6. The power consumption of both servers is the same before and after the relocation, but the change in outlet temperatures is notable. The calculation for $E_{cooling\_wasted}$ according to Eq. (14) shows that the server type B is wasting 22–24 watts per minute while server type A is not wasting any energy due to having a proper inlet temperature. As demonstrated in Table 5, after relocation, server type A has a lesser increase in outlet temperature as compared to inlet temperature increase.

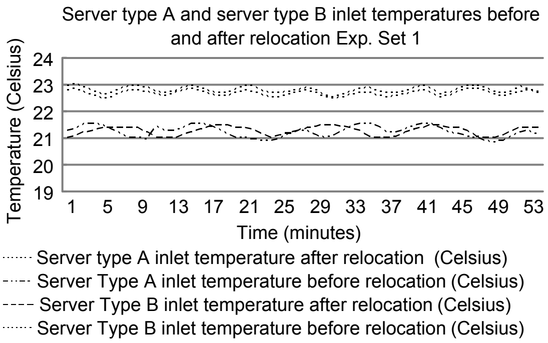

Fig. 3.4 The inlet temperatures at both locations remained almost the same

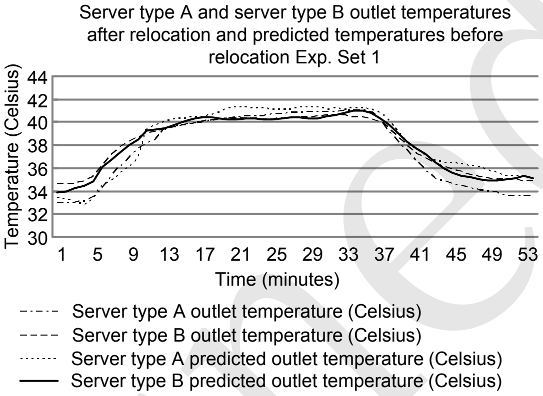

Fig. 3.5 The actual temperatures of the severs were within the predicted temperatures range

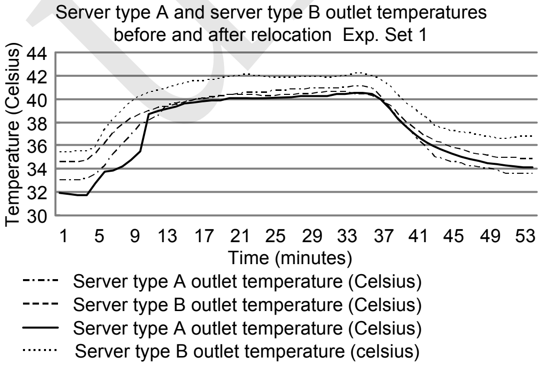

Fig. 3.6 The outlet temperatures of both server type are more homogenous after relocation

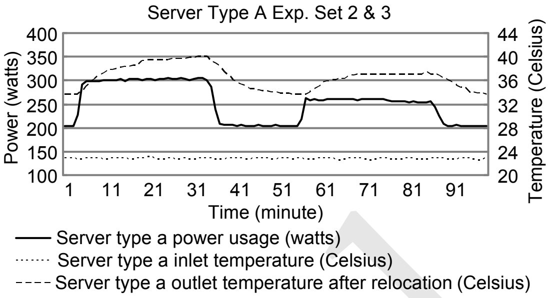

Fig. 3.7 The power consumption of server type A was the same as before relocation but the outlet temperature is higher after relocation

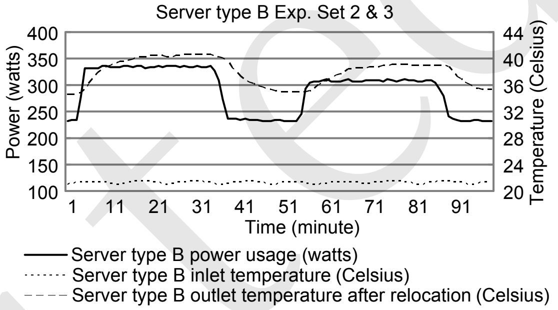

Fig. 3.8 The power consumption of server type B was the same as before relocation but the outlet temperature is lower after relocation

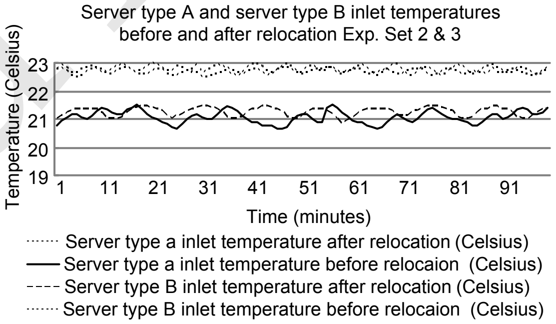

Fig. 3.9 The inlet temperature remained the same at both location as before relocation

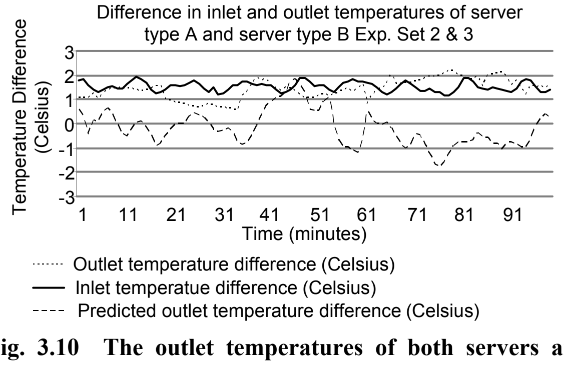

Fig. 3.10 The outlet temperatures of both servers are more homogenous after relocation. The fall in curve of exp. set 3 is due to server type B dissipating more heat than server type A even after relocation

Table 4 Summary of the experimental results before relocation.

Server type	Experiment set before relocation	Average Inlet (Celsius)	Average Outlet (Celsius)	Average computing power consumed (watts) per minute	$E^i_{computing}$ /$COP(T_{set})$ (watts) per minute	$E^i_{computing}$ / $COP(T_{received})$ (watts) per minute	$E_{cooling\_wasted}$ (watts) per minute	Total energy consumed (watts) per minute
A	1	21.2	38.7	329.0	94.0	94.0	0.0	423.0
B	1	22.7	41.3	336.0	96.0	84.0	24.0	444.0
A	2 & 3	21.2	37.0	276.0	79.0	79.0	0.0	355.0
B	2 & 3	22.7	40.7	320.0	91.0	80.0	22.0	422.0

Table 5 Summary of experimental results after relocation with calculations of decrease in cooling burden.

Server	Exp. set after relocation	Avg. inlet temperature (Celsius)	Avg. outlet temperature (Celsius)	Avg. computing power consumed (watts)	Difference in inlet temperatures before and after relocation (Celsius)	Difference in outlet temperatures before and after relocation (Celsius)	$E_{cooling\_wasted}$ saving (watts per minute)
A	1	22.8	39.4	328.0	+1.6	+0.7	11
B	1	21.2	39.6	333.0	−1.5	−1.7	24
A	2 & 3	22.7	37.2	280.0	+1.5	+0.2	10
B	2 & 3	21.2	39.0	321.0	−1.5	−1.7	22

Table 6 Decrease in occurrence of hotspots after relocation.

Exp. set	Difference between avg. outlet temperature before relocation (celsius)	Difference between avg. outlet temperature after relocation (celsius)	Percentage less chances of hotspot after relocation
1	2.6	0.2	77.0%
2 & 3	3.7	1.8	48.6%

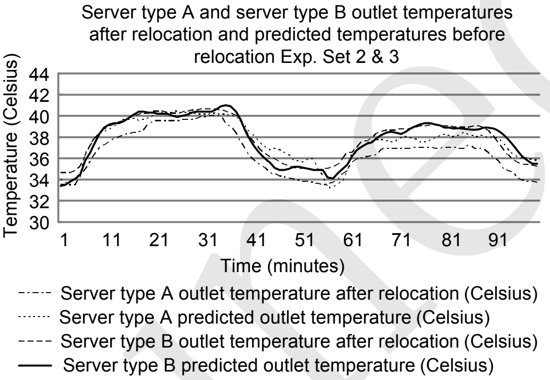

Fig. 3.11 The actual maximum temperatures of the severs were within the predicted temperatures range

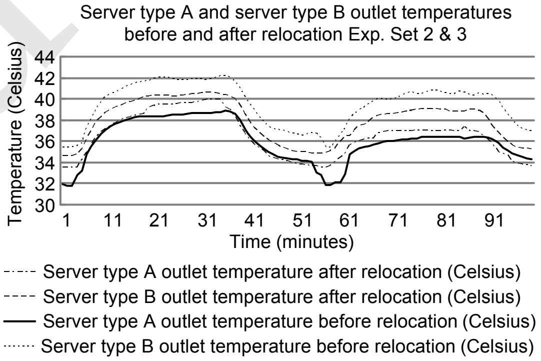

Fig. 3.12 The outlet temperatures of both server type are more homogenous after relocation

Therefore server type A compensated for increase in inlet temperature and therefore the $E_{cooling\_wasted}$ is reduced to half for server type A by as much as 11 watts. Server type B has no $E_{cooling\_wasted}$ due to lower inlet temperature.

Therefore the saving in $E_{cooling\_wasted}$ for server type B is from 22 to 24 watts as compared to Table 4. So overall the relocation process saves over 5% of the cooling energy for the relocated servers, which is over 2.1 kWh each for the working life of the servers. The relocation of servers brings homogeneity in outlet temperatures which reduces the chances of hotspots by up to 77.0% as shown in Table 6.

This can also be regarded as an improvement in cooling energy wastage. The proactive approach proposed in this paper saves the cooling energy that otherwise would be wasted on cooling a hotspot region. If the relocation algorithm is performed on the server sets after relocation, it will not predict favorable outlet temperatures from the servers. Hence the algorithm performs well in reducing the outlet temperature and chances of hotspots once implemented.

The total energy consumed after relocation is calculated and compared in Table 7. Since there is no major change in computing energy consumed before and after the relocation, therefore the cooling energy calculation on the basis of COP (Moore *et al*., 2005) will not show the lowering of cooling burden due to relocation and/or decrease in outlet temperature of the servers.

This is not only a limitation of the COP based calculation but also is challenging to prove through thermodynamics laws (Moore *et al*., 2005) (Qinghui *et al*., 2006).

This is because the thermodynamics laws are applied on the difference between the outlet and inlet temperatures for heat calculation and not on the intensity of the temperature. Deriving new thermal laws or thermal engineering equations for heat calculation is out of the scope of this paper. Therefore the cooling energy savings calculated in Table 6 are subtracted from the total energy consumed after relocation to mark the benefits of comparatively lower outlet temperature of the relocated server and the homogeneity of the outlet temperatures of the relocated servers. This is demonstrated in Table 7.

6.1 Recommendations for Server Relocation

Based upon the experiments and results, we present the best practices for server relocation inside data centers. These recommendations will help the data center managers to identify, analyze, predict and perform a relocation to save energy and to minimize cooling energy wastage.

- The chances of legitimate relocation requirement are higher between a set of servers where a subset of the server has higher inlet and outlet temperatures than another subset when all the servers are idle.
- If the server subsets have heterogeneous processors, then check the idle energy spent by the servers with hotter outlet is higher than the other subset. This will add to the chance of relocation as the higher outlet temperature at idle state may give rise to hotspot when servers are utilized.
- As a next step, the server subsets should be marked and put to experimental test load which boost the utilization of the servers' CPU to maximum and other underutilized levels. This step can be skipped if the daily usage of servers CPU is available covering a reasonable time. But this step is necessary if the servers are to be mounted for the first time. Data centers seldom keep the per minute performance records of thousands of servers and keep the aggregated records instead. Therefore, it is better to perform the exp. sets when there is an indication of inlet/outlet temperature variance.
- If there is more than one server in each subset then the relocation algorithm should be applied between all the combinations of paired servers by taking one server from each subset. The relocation algorithm gives the predicted temperatures of the pair of servers. This can reduce the complexity of comparing servers.
- Each server should be identified with the highest predicted change in inlet and outlet temperatures. To make server pairs, a good indicator is that both servers use the same amount of maximum electricity.
- Relocation is more favorable if a small change in inlet temperature can bring more change in outlet temperature. The ratio of CPU MHz and watts consumed is a supporting value for the predicted temperatures. A server having a low value of CPU MHz/watt will dissipate more heat than another server with higher CPU MHz/watt value if the

Table 7 Comparison of total energy consumption before and after relocation.

Server type	Experiment set	Avg. computing power consumed (watts)	$E^{i}_{computing}$ / $COP(T_{set})$ (watts) per minute	$E_{cooling_{wasted}}$ (watts) per minute	$E_{cooling_{wasted}}$ saving (watts per minute)	Total energy consumed after relocation (watts) per minute	Total energy consumed before relocation (watts) per minute
A	1	328.0	94.0	11.0	11	422.0	423.0
B	1	333.0	95.0	0.0	24	404.0	444.0
A	2 & 3	280.0	80.0	10.0	10	360.0	355.0
B	2 & 3	321.0	91.0	0.0	22	390.0	422.0

maximum power usage of both servers is equal to each other.

• It should be noted that at higher inlet temperature, the outlet temperatures rises at higher rate than at colder inlet temperature for the same server. The outlet temperatures of the relocated pair of servers should be more homogenous and the post relocation conditions defined earlier in the problem statement should be satisfied.

7 Conclusions

In this paper we presented an energy model to represent the cooling energy wastage by inlet temperature variations. The rise in inlet temperature can lead to hotspot causing increased outlet temperature of the data center servers. This increases the PUE of the data center due to energy wastage in cooling. This is highlighted through the data center energy modeling presented in this paper. The server relocation algorithm can successfully optimize the location of each server to lower the extra burden on the cooling mechanism. The proposed approach can lower the chances of hotspots and improves the cooling energy wastage by over 77%, lowers the cooling load through thermal-aware server relocation leads to energy saving by 2.1 kWh throughout the service time span of relocated servers and thus helps in establishing the green data centers. In short, the particular contributions of this paper are:

• An energy model was presented to explain the effect of rise in inlet temperature of each server and the effect of this upon total power consumption of the data center.

• A proactive algorithm for server relocation is presented to:

—Avoid hotspots

—Lower the peak temperature of hot air from the outlets of the relocated server set.

—Homogenize the outlet temperatures of the set of relocated servers

These will result in lower cooling load, avoidance of hotspots, ensuring equipment safety and help in maintaining green data centers.

• Recommendations or best practices for server relocation are presented which will help the data center managers to identify, analyze and perform a relocation to save power and to minimize cooling power wastage.

Conflict of Interest

The authors have no conflict of interest and all authors agreed on submission and publication of this manuscript in Journal of Zhejiang University-SCIENCE C (Computers & Electronics).

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