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MODELING AND CONTROL OF DATA CENTER POWER CONSUMPTION MINIMIZATION STRATEGIES

Urgency of the research. Optimization of data center power utilization by getting a proper proportion of computing and cooling power consumption reducing as an important problem of modern engineering science was discussed. It was shown that energy-efficiency constraints problem as a main limiting factor for data centers performance can be solved by thermal modeling and control solutions development.

Target setting. Recent studies analysis shows that hybrid cooling solutions which nowadays widely used in a data centers require to provide analysis of virtual machines structure organization and utilize higher cooling capability due to the high operating temperature of active servers.

Actual scientific researches and issues analysis. Thereby it is necessary to develop computational and cooling power consumption optimization solution for hybrid cooling architecture. It will allow to achieve overall power loss minimization with satisfying of service-level agreement requirements.

Uninvestigated parts of general matters defining. For determination of chillers work schedule it is necessary to estimate power consumption of datacenter, cooling mode transition overheads, number of servers, virtual machines and its placement.

The statement of basic materials. There were compared three cooling mode solutions for data centers: fixed temperature regime, P-adaptive regime and PT-adaptive regime. Fixed temperature regime as conventional cooling mode which uses free cooling only when output temperature is lower than pre-defined temperature was proved to be inefficient while P-adaptive regime and PT-adaptive regime was proved to be preferable ones.

The research objective. Proposed solution significantly extends the usability of free cooling for data centers, while it takes into account climate condition, servers' workload, server room's temperature profile and server cooling architecture.

Conclusions. Therefore developed model of cooling mode efficiency estimation allowed recommending PT-adaptive regime as adaptive mode which jointly optimizes the power consumption and transition overhead.

Keywords: data center; power consumption; virtual machine; free cooling mode; electrical cooling mode; fixed temperature regime; PT-adaptive regime.

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МОДЕЛЮВАННЯ ТА УПРАВЛІННЯ СТРАТЕГІЯМИ МІНІМІЗАЦІЇ ЕНЕРГОСПОЖИВАННЯ ЦЕНТРУ ОБРОБКИ ДАНИХ

Актуальність теми дослідження. Обговорено методи оптимізації використання енергоспоживання центрів обробки даних шляхом визначення належних пропорцій між витратами на систему охолодження та обчислювальну систему, що на сьогоднішній день є важливою проблемою інженерної науки та інформаційних технологій. Показано, що проблема обмеження енергоефективності як основного обмежувального фактора для роботи центрів обробки даних може бути вирішена шляхом розробки термічного моделювання та управління.

Постановка проблеми. Аналіз сучасних досліджень у даній галузі показав, що гібридні охолоджувальні рішення, які сьогодні широко використовуються в центрах обробки даних, вимагають визначення оптимальної організації комплексу віртуальних машин і застосування більш ефективної системи охолодження у зв'язку з високим рівнем робочої температури активних серверів.

Виділення недосліджених частин загальної проблеми. Таким чином, була показана необхідність розроблення рішення для оптимізації використання обчислювальної системи та гібридної системи охолодження. Це дозволяє досягти мінімізації загальної втрати потужності задовольняючи вимоги до угоди про рівень обслуговування центру обробки даних.

Постановка завдання. Запропоноване рішення значно розширює зручність охолодження для центрів обробки даних, враховуючи кліматичні умови, навантаження серверів, температурний режим сервера та архітектуру системи охолодження сервера.

Виклад основного матеріалу. Було проведено порівняння трьох типів режиму охолодження для центрів обробки даних: фіксований температурний режим, P-адаптивний режим та PT-адаптивний режим. Фіксований режим температури, як звичайний режим охолодження, який використовує вільне охолодження тільки тоді, коли вихідна температура нижче заданої температури, виявився неефективним, тоді як P-адаптивний режим і PT-адаптивний режим можуть бути використані у рамках розробленої методології.

Висновки відповідно до статті. Таким чином, розроблена модель оцінки ефективності режиму охолодження дозволила рекомендувати PT-адаптивну схему, що найбільшою мірою оптимізує процес споживання енергії.

Ключові слова: центр обробки даних; споживання електроенергії; віртуальна машина; режим вільного охолодження; режим електро-охолодження; режим фіксованої температури;PT-адаптивний режим.

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МОДЕЛИРОВАНИЕ И УПРАВЛЕНИЕ СТРАТЕГИЯМИ МИНИМИЗАЦИИ ЭНЕРГОПОТРЕБЛЕНИЯ ЦЕНТРА ОБРАБОТКИ ДАННЫХ

Актуальность темы исследования. Обсуждены методы оптимизации использования энергопотребления центров обработки данных путем определения надлежащих пропорций между затратами на систему охлаждения и вычислительную систему, на сегодняшний день является важной проблемой инженерной науки и

информационных технологий. Показано, что проблема ограничения энерго-эффективности как основного ограничительного фактора для работы центров обработки данных может быть решена путем разработки термического моделирования и управления.

Постановка проблемы. Анализ современных исследований в данной области показал, что гибридные охлаждающие решения, которые сегодня широко используются в центрах обработки данных, требуют определения оптимальной организации комплекса виртуальных машин и применения более эффективной системы охлаждения в связи с высоким уровнем рабочей температуры активных серверов.

Выделение неисследованных частей общей проблемы. Таким образом, была показана необходимость разработки решения для оптимизации использования вычислительной системы и гибридной системы охлаждения. Это позволяет достичь минимизации общей потери мощности удовлетворяя требования к соглашению об уровне обслуживания центра обработки данных.

Постановка задачи. Предложенное решение значительно расширяет удобство охлаждения для центров обработки данных, учитывая климатические условия, нагрузки серверов, температурный режим сервера и архитектуру системы охлаждения сервера.

Изложение основного материала. Было проведено сравнение трех типов режима охлаждения для центров обработки данных: фиксированный температурный режим, P-адаптивный режим и PT адаптивный режим. Фиксированный режим температуры, как обычный режим охлаждения, который использует свободное охлаждение только тогда, когда исходная температура ниже заданной температуры, оказался неэффективным, тогда как P-адаптивный режим и PT-адаптивный режим могут быть использованы в рамках разработанной методологии.

Выводы соответствии со статьей. Таким образом, разработана модель оценки эффективности режима охлаждения позволила рекомендовать PT-адаптивную схему, в наибольшей степени оптимизирует процесс потребления энергии.

Ключевые слова: центр обработки данных потребление электроэнергии; виртуальная машина; режим свободного охлаждения; режим электро-охлаждения; режим фиксированной температуры; PT адаптивный режим.

1. Introduction

Data center power utilization level optimization by getting a proper proportion of computing and cooling power consumption reducing is a *hot spot of modern engineering science and information technologies (IT)*. Usually conventional computing power minimization solutions lead to actual CPU utilization increase and require higher cooling capability in order to work with increased heat density of active servers. Nowadays hybrid cooling solutions are widely used in a datacenters [1-3], which requires to provide further analysis of virtual machines (VM) structure organization and reduces the chance of using free cooling; hybrid cooling schemes usually require high cooling capability due to the high operating temperature of active servers [4-8].

Therefore joint computational and cooling power consumption optimization solution for datacenters as a *target of the research* was proposed (Figure 1). It was developed for hybrid cooling architecture and allows to achieve overall power loss minimization with satisfying of service-level agreement (SLA) requirements. To identify the main aspects of the joint power consumption optimization model development, *systematic analysis of recent studies and publications* was done. There were analyzed modern cooling solutions for cloud services [1-3], VM placement schemes and free cooling system check [4-8]. Statistics of the climate condition and servers' workload [9-11] allowed forming requirement or predictive control scheme development. Computational algorithms that can be used for server room's temperature profile simulation [12-18] were also discussed.

It was shown lack of unified methodology which allows to significantly extend the usability of free cooling for data centers having a hybrid cooling architecture as *uninvestigated part of discussed studies*. Proposed solution takes into account all input parameters of data center server room infrastructure, specifically climate condition, servers' workload, server room's temperature profile and server cooling architecture.

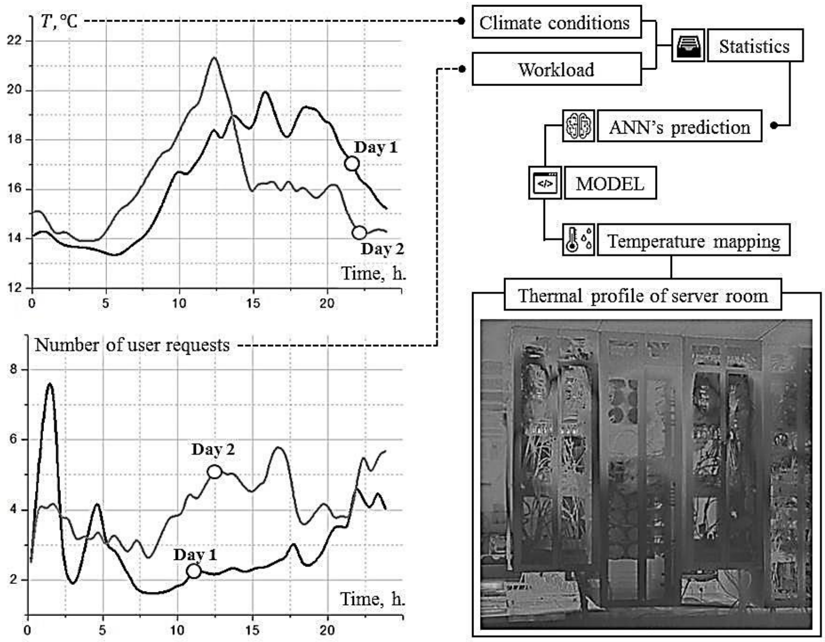


Fig. 1. **Joint power consumption optimization scheme for hybrid cooling architecture.**

Statistics of the climate condition and servers' workload forms artificial neural network (ANN) training dataset and further can be forecasted by predictive control scheme. In other hand server room's temperature profile and the dependency between the server temperature and cooling solutions can be simulated and modeled by standard algorithms. Thus, the *research objective* implies to development of combined scheme and unified methodology for data center hybrid cooling architecture.

2. Proposed method

Development of combined scheme and unified methodology for data center hybrid cooling architecture implies to build joint power consumption optimization model. It is necessary to estimate optimal cooling mode regime and maximum power consumption of active servers. It allows determining chillers work schedule in order to have no overheads in terms of power and time. Main parameters to be analyzed are:

- power consumption of datacenter P_{DC};
- cooling mode transition overheads P_{TR};
- number of servers N_S;
- number of VMsN_{VM};
- binary matrix representing VM placement $B(i,j)$;
- binary parameter CM which determines cooling mode (CM = 0 for electrical cooling and CM = 1 for free cooling).

Power consumption of datacenter can be calculated as

$$P_{DC} = P_{Cool} + P_{Comp}, \tag{1}$$

where P_{Cool} refers to power consumption of cooling system and P_{Comp} represents computational power consumption.

Mathematically the problem solving aspects can be formulated as determining of $B(i,j)$ and CM parameter by obtaining minimums of objective function of entire power consumption P_{Σ} (Figure 2):

$$\begin{cases} B(i,j) = \begin{bmatrix} b(1{,}1) & \cdots & b(1{,}1) \\ \cdots & \cdots & \cdots \\ \cdots & b(i,j) & \cdots \\ \cdots & \cdots & \cdots \\ b(N_S{,}1) & \cdots & b(N_S, N_{\mathrm{VM}}) \end{bmatrix} \\ CM \in [0;1] \\ P_{\sum} = P_{\mathrm{DC}} + P_{TR} \end{cases} \qquad (2)$$

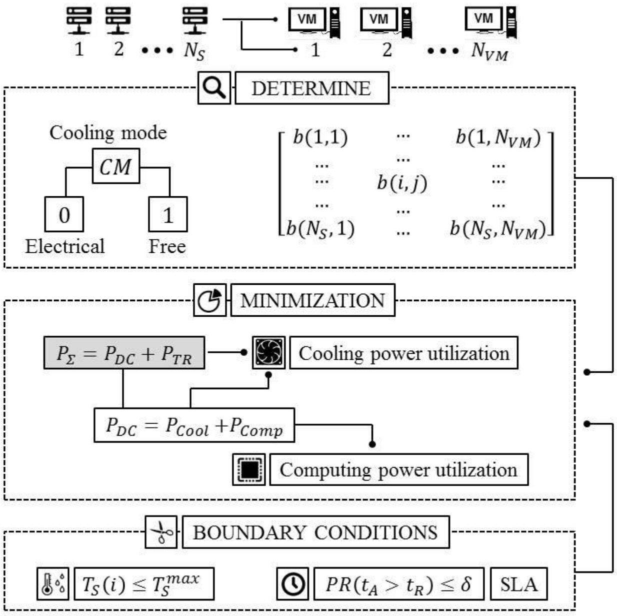


Fig. 2. **Mathematical algorithm of joint power consumption scheme for hybrid cooling architecture.**

It has to be noticed that obtaining minimums of objective function minimum should also include analysis of boundary conditions for server temperature and server performance.

For boundary conditions estimation on should found $T_S(i)$ which refers to temperature of i -th server and probability $PR()$ of actual execution time t_A exceeding required execution time t_R:

$$\begin{cases} T_S(i) \le T_S^{\max} \\ PR(t_A \succ t_R) \le \delta \end{cases} \qquad (2)$$

where $T_S^{\max}$ is maximum temperature constraint for data center servers and is δ SLA requirement parameter. Thereby optimization problem can be translated into a bin-packing problem by exploiting the analogy between a bin and a server.

3. Experimental results and analysis

To simplify developed methodology two-phase algorithm can be proposed. It includes determination of optimal pair of parameters of cooling regime and active servers' utilization threshold level $\{CM; U_S^{TH}\}$ which allows to satisfy temperature and performance requirements (3). At the second stage VMs have to be assigned to servers in order to minimize number of servers. Optimization procedure should be iterated at every predefined time interval. Thereby equations (2) and (3) could be estimated as:

$$\begin{cases} B(i,j) \in \left[0, U_S^{TH}\right]; CM \in [0;1] \\ P_{\sum}(k) = \sum_{i=\kappa}^{\kappa+N_T-1} a^{i-\kappa} \cdot (P_{Cool}^{PR} + P_{TR}^{PR}) \end{cases} \quad (4)$$

and boundary conditions could be defined as:

$$\begin{cases} U_S^{TH}(l) \geq \widehat{U}_R / N_S \\ l \in [k, k+N_S-1] \end{cases}, \quad (5)$$

$$\begin{cases} U_S^{TH} \leq \min(U_S^{\max}, U_S^T(l)) \\ \forall l, 1 \leq a \leq 0 \end{cases}, \quad (6)$$

where

- N_T is number of time periods;
- P_{Cool}^{PR}, P_{Comp}^{PR} and P_{TR}^{PR} are predicted values of P_{Cool}, P_{Comp} and P_{TR} values at the l -th time period;
- $\widehat{U}_R$ is the prediction of average user requests normalized with maximum number of user requests for single server;
- a is a weighting factor;
- $U_S^{\max}$ is maximum acceptable performance loss regime power;
- $U_S^T(l)$ is highest utilization satisfying maximum temperature constraint.

Figure 3 shows dependence of the power consumption on the U_S^{TH} value. Figure demonstrates that total power consumption at free cooling mode is usually changes in proportion to computing power as U_S^{TH} increase is more significant than the cooling power consumption growth. However, the cooling capability of the free cooling is limited, and maximal value of U_S^{TH} for this cooling mode is also limited.

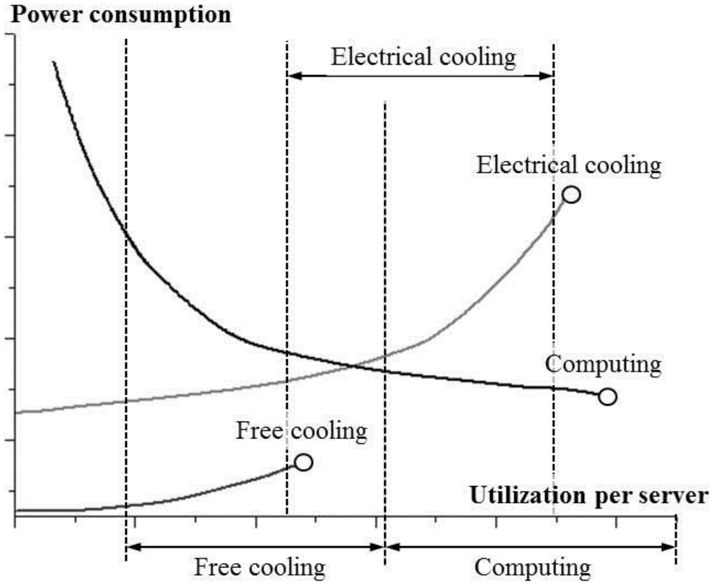


Fig. 4. **Dependence of the power consumption on the active servers' utilization threshold level for free cooling and electrical cooling regimes.**

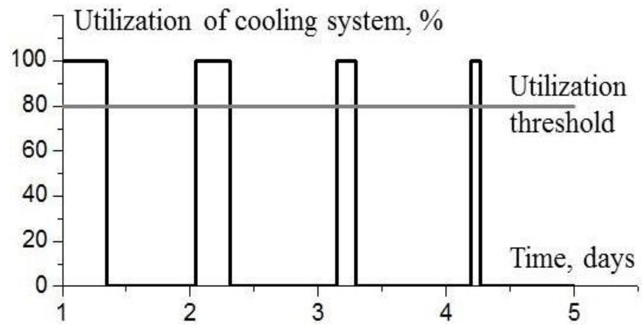
To evaluate the effectiveness of the joint optimization model statistical dataset of CloudSim simulation [19] was used (Figure 5). There were compared three cooling mode solutions for data centers:

- fixed temperature regime as conventional cooling mode which uses free coolingonly when output temperature is lower than pre-defined temperature $(U_S^{TH} = U_S^{\max})$;
- P-adaptive regime as adaptive mode which adjusts the cooling and the utilization threshold to minimize power consumption of data center;
- PT-adaptive regime as adaptive mode which jointly optimizes the power consumption and transition overhead.

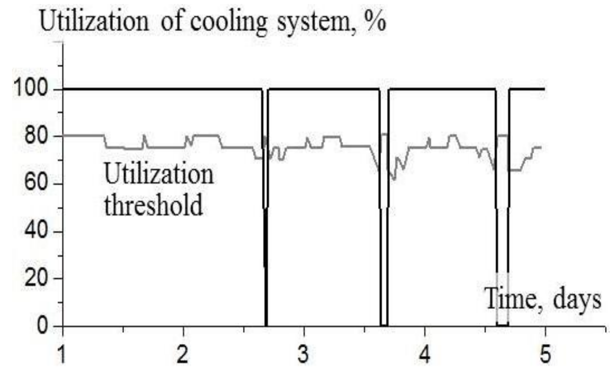
The highest power consumption savings were observed at comparison of fixed temperature regime and P-adaptive regime while output temperature was usually higher pre-defined temperature so free cooling mode utilization was usually impossible. In other hand PT-adaptive regime allowed to use free cooling mode by lowering the maximum server power consumption.

Comparison of P-adaptive and PT-adaptive regimes has shown almost similar level of power consumption savings. However, PT-adaptive regime allowed to significantly decrease number of cooling modes transitions by accounting for the overhead caused by the cooling mode transitions. It is important to notice that the effectiveness of PT-adaptive gets enhanced as the power consumption proportion of servers gets to be improved.

Normalized power consumption as the power proportionality of servers should be defined as the ratio of the static power P_{ST} to the total power consumption P_{Σ}. For low value of P_{ST}/ P_{Σ} can be used free cooling for longer periods of time due to lower server utilization threshold. Thereby minimal number of active servers can be used and developed methodology can be used to achieve higher energy-proportionality. Experiments' simulation statistics datasets demonstrates that PT-adaptive allows to provide higher level of power consumption savings for datacenter infrastructure.



(a)



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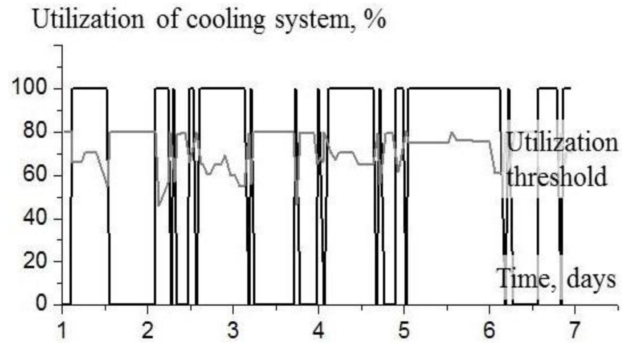

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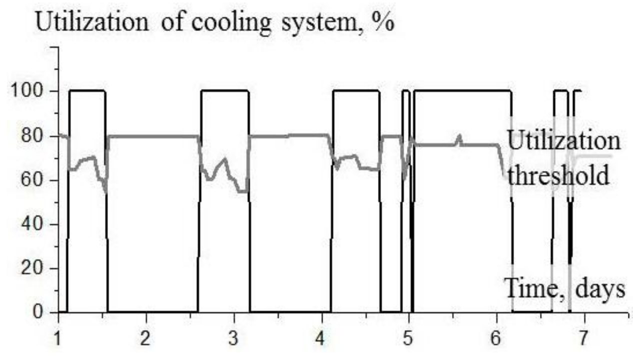
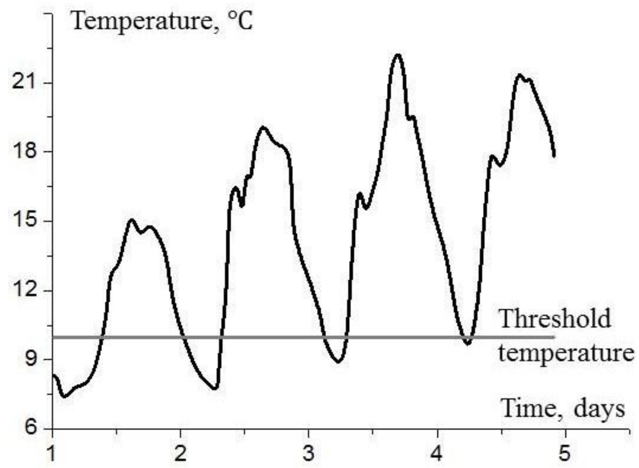
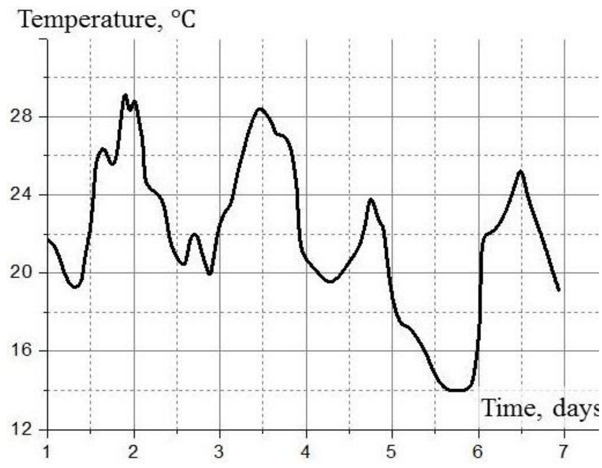


(e)



(c)



(f)

Fig. 6. **Comparison of power utilization of fixed temperature (a) and PT-adaptive (b) cooling modes at temperature regime "1" (c) and power utilization of P-adaptive (d) and PT-adaptive (e) cooling modes at temperature regime "2" (f).**

Thereby energy-efficiency constraints problemasa main limiting factor for datacenters performance can be solved by thermal modeling and control solutions development which have to be considered as key aspect of power consumption reducing.

4. Conclusions

Key aspects of data center power utilization optimization by getting a proper proportion of computing and cooling power consumption reducing were analyzed. Energy-efficiency constraints problem have to be be solved by thermal modeling and control solutions development. While nowadays hybrid cooling solutions are widely used in a data centers it is important to provide analysis of virtual machines structure organization and utilize higher cooling capability due to the high operating temperature of active servers. It allows to achieve overall power loss minimization with satisfying all requirements.

Proposed methodology extends the usability of free cooling for data centers. It takes into account climate condition, servers' workload, server room's temperature profile and server cooling architecture. It was demonstrated that for development joint power consumption optimization model it is necessary to estimate optimal cooling mode regime and maximum power consumption of active servers. For determination of chillers work schedule were estimated power consumption of datacenter, cooling mode transition overheads, number of servers, virtual machines and its placement. There were compared three cooling mode solutions for data centers: fixed temperature regime, P-adaptive regime and PT-adaptive regime. Fixed temperature regime was shown as inefficient one while P-adaptive regime and PT-adaptive regime was proved to be preferable ones. Developed model of cooling mode efficiency estimation demonstrated preferences of PT-adaptive regime as adaptive mode which jointly optimizes the power consumption and transition overhead.

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