Analytical model of data center infrastructure efficiency for system level simulations

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ABSTRACT

Data center energy efficiency has risen to the forefront within a short period of time. Efficiency improvements can have significant economical and environmental effects; hence, they are actively sought out by data center operators. Developing techniques and associated tools for the evaluation of overall data center efficiency is therefore a pivotal research area. Ability to evaluate the efficiency of existing and especially emerging solutions and technological advances requires methods capable of predicting the energy use at a fundamental level. Analytical modeling and numerical simulations are the key techniques for these tasks. This paper studies high-level, analytical methods for modeling the total data center energy efficiency, and evaluates the opportunities such models provide for simulations. Polynomial efficiency models for cooling and power-conversion equipment are used to construct system-level simulation models for various powering schemes. And these models are applied in example cases to demonstrate benefits of the proposed modeling approach.

Categories and Subject Descriptors

C.4 [**Performance of Systems**]: Modeling techniques; C.5.0 [**Computer System Implementation**]: General; I.6.5 [**Simulation and Modeling**]: Model development—*modeling methodologies*

General Terms

Design, Performance, Theory

Keywords

Data center, Energy efficiency, UPS, Simulation model

1. INTRODUCTION

Data centers, and ICT in general, have become one of the pivotal cornerstones of modern society. Within a short period of time, use of and reliance on ICT has grown drastically. In spite of steady improvements in semiconductor and cooling technology, total data center energy consumption has also grown rapidly. Energy efficiency of data centers and ICT systems has therefore become a prominent research topic with promises for both economical and environmental savings [8].

Understanding data center's efficiency is pivotal in order to be able to minimize its energy usage. This, however, is difficult for a number of reasons. Basic challenge in evaluating these systems comes from the variety of solutions and the large number of different types of equipment. Moreover, varying operating conditions and system parameters complicate the setup further. A more profound challenge comes from the complex behavior of the equipment themselves, which are characterized by almost exclusively nonlinear behavior for all the major system components [8].

Developing simulation models and methods for data center infrastructure provides key efficiency evaluation tools for people designing and operating data centers. These tools allow to assess the impact and effects of hardware changes, varying operating conditions and dimensioning of the design, amongst others. Furthermore, these tools allow research communities to evaluate new and emerging ideas and technologies.

While research on simulation and modeling, which touches at least partially on efficiency, has been made, it is almost exclusively focused on subsystems, such as cooling or servers [2] [9]. Studies that combine all important components and generate the results for the overall efficiency are nonexistent and therefore, urgently required [6].

In this paper, we will focus on modeling and simulating the total data center efficiency. Our primary interest is to evaluate the ratio between server and total system input power and how this ratio behaves between different hardware and setups. In order to achieve this, we will construct nonlinear models for the most important components and equipment, and furthermore, capture their interaction for the construction of system level simulation models.

This paper is divided as follows. We will first discuss data center power infrastructure and various topologies in Section II. In Section III, we will form polynomial efficiency models first for cooling and UPS units and then combine these to form simulation models for the various topologies. In Section IV, we will employ the models to simulate illustrative example schemes. In Section V, we will summarize the results and discuss the implications together with some of the limitations of the proposed models.

2. DATA CENTER INFRASTRUCTURE

Data center equipment is traditionally divided into three primary groups of cooling, power distribution and IT equipment. IT equipment, most often servers, are the main component of data center, while the cooling and power distribution components are supportive, required for the operation of the IT equipment [8]. We will use the terms IT and servers interchangeably in this paper.

Cooling equipment is needed to remove the heat generated mainly

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in the IT equipment, but also in the power distribution and cooling components themselves. Power distribution components are required to route power from the utility grid to the IT and cooling equipment.

All of the aforementioned components consume power and hence impact on the data center efficiency. However, the cooling and power distribution are undesired sources for energy use, since they do not directly provide computing services. For high efficiency, their consumption should therefore be minimized. The two groups embody a number of different equipment, of which the most power consuming devices are considered to be the UPS units for the power distribution and chillers for the cooling equipment. For the typical air-cooled data center, fan power in servers and computer room air conditioning units (CRACs) is also a significant factor. Here, we will use the term CRAC to mean any kind of cooling devices.

The fundamental challenge in assessing data center efficiency lies in the fact that all these components affect each other. Their relationships depend on the way the data center is designed and operated. Analyzing these designs is hence an important aspect of improving efficiency.

Data center power arrangements have become very standardized. Power is distributed from utility grid through UPS units to the servers to guarantee reliable power. For the cooling and other equipment, power can be routed either through a UPS, or directly from the grid. The former provides more reliability, while the latter provides better efficiency and possibly lower equipment costs [8]. The necessity for UPS backed cooling has been discussed for example in [10]. It should be noted that server fans are usually powered via the server supply and are hence UPS backed. It is also possible to separate UPS units for cooling and servers.

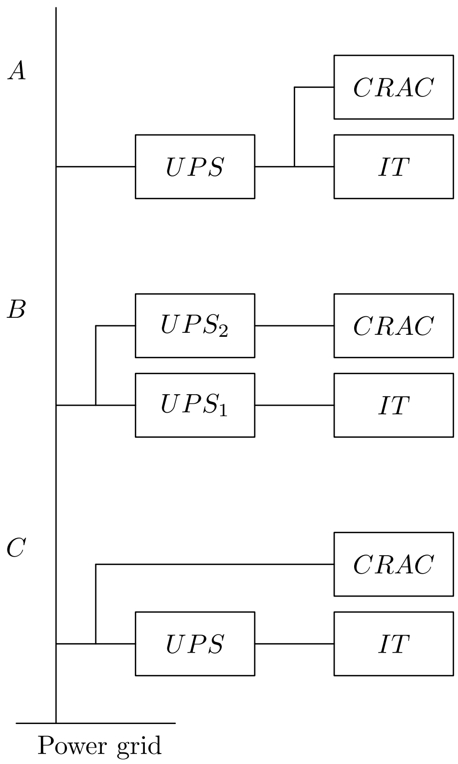

Figure 1: Three fundamental power distribution topologies of interest.

The three fundamental power distribution topologies, A, B and C, are depicted in Fig. 1. In order to model total data center efficiency, power flow for a given topology has to be understood.

3. ANALYTICAL EFFICIENCY MODELS

Data centers typically comprise hundreds or thousands of servers and a large number of the various auxiliary equipment. Including each individual component would result in models with a very large number of parameters. We could, for example, divide the workload equally among the devices, or utilize some parts fully, while others are idling. Optimal workload allocation is an active research topic that exemplifies this problem [11]. We could also rely on statistical methods by averaging the effect of different loading conditions across the equipment. As a third option, we could assume that the workload is equally divided among each equivalent component and hence we can use a lumped model for system level simulations. The two latter approaches are more pragmatic, since they provide more general solutions. It should also be noted that, in order to study issues such as the optimal workload allocation, we need to model the basic component level interaction, as well. Development of general models which can be modified for specific use cases is therefore to be preferred. Hence we will limit our scope in this paper to lumped simulation models, in which similar components are considered as a single unit.

Including all possible parameters and variables that affect the data center in the system models would render the models complex. Moreover, there is a trade-off between accuracy and complexity that needs to be considered.

In order to keep the models compact, we will focus only on active components, that is, components and equipment that use power, such as fans, power conversion stages and IT equipment. We will leave passive components, such as heat exchangers, outside our model scope. It is very likely that we need to construct different models for different operating conditions. Alternatively, operating conditions, such as temperatures, could be embedded in the component models as parameters, as is done in [2]. We will also omit certain power distribution components that, while passive, cause losses. These include cabling and switches. These losses are quadratic in nature and could be included in the UPS component, which also exhibits quadratic conduction losses [5].

We also assume that all the component models exhibit monotonic power losses, that is, the power consumed in the devices grows continuously as a function of utilization.

3.1 Component models

Component model complexity needs to be considered from a practical perspective; high complexity of equipment models may render it difficult to gather enough data for parameterizing the models. In many cases, it would be desirable if we could parameterize the models directly from manufacturer data. Our solution is flexible, since it is based on polynomial models, the order of which could be adjusted for the accuracy needs of a specific case.

3.1.1 UPS model

Manufacturers typically give data for their UPS equipment in a form of a curve that depicts efficiency as a function of the load percentage. This curve varies between UPS types, but is nonlinear and designed to provide high efficiency at higher loads. The efficiency decreases drastically when the output power approaches zero.

We could directly model this nonlinear efficiency curve for use in calculations. However, we can also present the power loss in the UPS as a function of the UPS load. Hence the basic power flow for

UPS would follow the equation

$$P_{Ui} = P_{Ul} + P_{Uo}, \quad (1)$$

where P_{Ui} is the input and P_{Uo} the output power. P_{Ul} is the power loss due to the finite conversion efficiency. As presented in [5], UPS efficiency and consequently the power loss can be accurately modeled with a second order polynomial, such as

$$P_{Ul} = K_0 + K_1 L_{load\%} + K_2 L_{load\%}^2, \quad (2)$$

where L_{load} is the load level as a percentage of the rated active power. Coefficients K_n define the shape of the power loss curve for a given UPS unit. $L_{load\%}$ can be expressed as

$$L_{load\%} = \frac{P_{Uo}}{P_{Ud}}, \quad (3)$$

where P_{Ud} is the peak output power of the UPS unit and hence a design parameter. Combining (2) and (3) results in a normalized loss equation

$$P_{Ul} = K_0 + K_1 \frac{P_{Uo}}{P_{Ud}} + K_2 (\frac{P_{Uo}}{P_{Ud}})^2 \quad (4)$$

To get from the normalized power loss to the actual power loss, we need to multiply the result by the peak design power. Hence we get

$$P_{Ul} = K_0 P_{Ud} + K_1 P_{Uo} + K_2 \frac{P_{Uo}^2}{P_{Ud}} \quad (5)$$

This provides us with a model in which the characteristic efficiency is separated from the nominal design peak power. Hence we can select an efficiency model of interest and then freely scale the UPS size for a given setup. Combining equations (1) and (5) we can present the UPS input-output relationship as

$$P_{Ui} = K_0 P_{Ud} + K_1 P_{Uo} + K_2 \frac{P_{Uo}^2}{P_{Ud}} + P_{Uo}. \quad (6)$$

3.1.2 Cooling model

As noted in [1], polynomial models have been widely utilized when calculating typical cooling system energy use and they provide adequate accuracy. For modeling the cooling system, we are focused on two actively power consuming components; fans and compression chillers. As noted in [3], these two dominate the cooling power usage.

Polynomial chiller models have been discussed, for example, in [2] and [7], showing that sufficient accuracy can be achieved with second or third order polynomials.

Studies in [12] and [1] discuss the use of second and third order polynomials for fan power modeling. Third order models generally provide good accuracy. Benefits of higher order models are evaluated in [13].

We will use a third order polynomial for cooling component model, which gives us the relationship between required heat removal rate Q_t and the cooling power consumption P_{Ci}. The model is of the form

$$P_{Ci} = N_0 Q_{Cd} + N_1 Q_t + N_2 \frac{Q_t^2}{Q_{Cd}} + N_3 \frac{Q_t^3}{Q_{Cd}^2}, \quad (7)$$

where Q_{Cd} is a design parameter that presents the peak heat removal rate of the equipment and coefficients $N_{0,1,2,3}$ define the characteristic component behavior.

3.2 System level models

Next we will construct system level models for the three cases of power distribution topologies presented in Fig. 1. The power and heat flows for cases A and B are presented in Fig. 2.

An important parameter that we need to assess is what contributes to the heat load for the system. It is possible that some of the equipment do not need cooling, if they are, for example, located outside the data center. However, the case in which all the equipment constitute to the heat load is the most complex case and therefore we will assume this approach.

3.2.1 Case A

For the Case A, we can start by noting that the total power P_t consumed in the system goes through the UPS. Hence,

$$P_t = P_{Ui}, \quad (8)$$

Output from the UPS is the sum of power consumed by the servers and cooling system.

$$P_{Uo} = P_{Si} + P_{Ci}, \quad (9)$$

where, P_{Si} is the server input power. Our heat removal rate is the sum of power consumed in each component, hence

$$Q_t = P_{Ci} + P_{Ul} + P_{Si} \quad (10)$$

Combining equations (1), (6), (7), (8), (9), (10) and eliminating variables P_{Ul}, P_{Ci}, P_{Ui}, P_{Uo} and Q_t we get

$$\begin{aligned} Q_{Cd}^2 P_{Ud} (Q_{Cd}^2 (((K_1+1)N_1 - 1)P_{Ui} + (K_1+1)P_{Si} \\ + K_0 P_{Ud}) + (K_1+1) N_2 Q_{Cd} P_{Ui}^2 + (K_1+1) N_0 Q_{Cd}^3 \\ + (K_1+1) N_3 P_{Ui}^3) + K_2 (Q_{Cd}^2 (N_1 P_{Ui} + P_{Si}) \\ + N_2 Q_{Cd} P_{Ui}^2 + N_0 Q_{Cd}^3 + N_3 P_{Ui}^3)^2 = 0, \quad (11) \end{aligned}$$

which represent the relationship of server input power to the total input power as a function of the UPS and cooling model parameters.

3.2.2 Case B

The system efficiency for Case B is similar to the Case A. This time, however, we have two UPS units and the total power is the sum of inputs to the UPS units. Hence,

$$P_t = P_{Ui} + P_{U2i}, \quad (12)$$

where P_{U2i} is input power for the cooling dedicated UPS. Furthermore, we can equate the server input and the cooling input to the respective UPS output powers:

$$P_{Uo} = P_{Si} \quad (13)$$

$$P_{U2o} = P_{Ci} \quad (14)$$

Inserting equations (13) and (14) into (1), we get

$$P_{Ui} = P_{Uo} + P_{Ul} = P_{Si} + P_{Ul}, \quad (15)$$

and

$$P_{U2i} = P_{U2o} + P_{U2l} = P_{Ci} + P_{U2l} \quad (16)$$

Since we now have two UPS units, we need to include the losses for both, and the total heat removal rate becomes

$$Q_t = P_{Ci} + P_{Ul} + P_{U2l} + P_{Si} \quad (17)$$

Combining equations (12), (15), (16) and (17) with the component models (6) and (7) and eliminating variables P_{Ul}, P_{U2l}, P_{Ci}, P_{Ui},

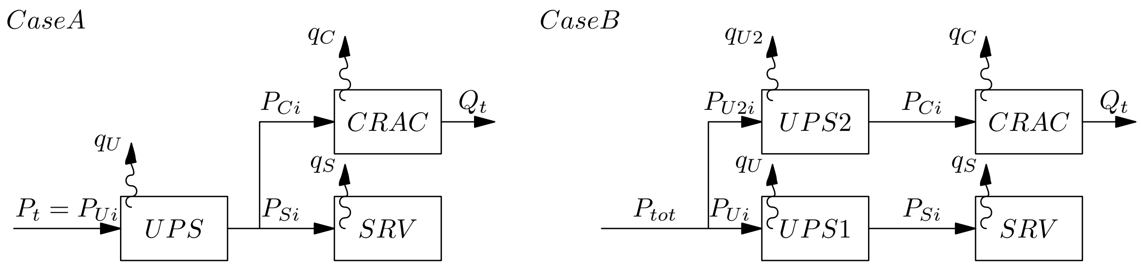

Figure 2: Power flows for the two different topologies A and B. The third topology, in which cooling is directly routed to the power grid, can be deduced from the topology B on the right, by noting that the efficiency of cooling UPS in this case is 1.

P_{Uo}, P_{U2o} and Q_t we get

$$\begin{aligned}P_{Ud}(Q_{Cd}^2 P_{U2d}(Q_{Cd}^2(((k_1+1)N_1-1)P_t + k_0 P_{U2d} \\ + (K_1+1)P_{Si} + K_0 P_{Ud}) + (k_1+1)N_2 Q_{Cd} P_t^2 \\ + (k_1+1)N_0 Q_{Cd}^3 + (k_1+1)N_3 P_t^3) \\ + k_2(P_t(P_t(N_2 Q_{Cd} + N_3 P_t) + N_1 Q_{Cd}^2) \\ + N_0 Q_{Cd}^3)^2) + K_2 Q_{Cd}^4 P_{Si}^2 P_{U2d} = 0, \quad (18)\end{aligned}$$

which represent our Case B relationship of power flow as function of the UPS and cooling design parameters. Lower-case coefficients $k_{0,1,2,3}$ in (18) represent the model coefficients for the cooling UPS.

3.2.3 Case C

System model for Case C, where the cooling is routed directly to the supply grid, can be constructed like the two previous cases. However, since the Case C is a special case of Case B, where the cooling UPS unit efficiency is 1, we can get the result directly from equation (18) by setting the coefficients $k_{0,1,2,3}$ to zero. This yields the equation

$$\begin{aligned}P_{Ud}(P_{Cd}^2((K_1+1)P_{Si} + K_0 P_{Ud} + (N_1-1)P_t) \\ + N_2 P_{Cd} P_t^2 + N_0 P_{Cd}^3 + N_3 P_t^3) + K_2 P_{Cd}^2 P_{Si}^2 = 0, \quad (19)\end{aligned}$$

for the topology in Case C.

3.2.4 Solving power flows

Equations (11), (18) and (19) can be solved for, e.g., server input power as a function of total input power. Resulting solutions may become complex to manipulate. Solving and using them may benefit of software capable of symbolic calculations. Equations (28), (29) and (30) in Appendix A depict solutions to the aforementioned server power to the total power relationships for each of the three topologies.

4. APPLICATION EXAMPLES

System-level models derived in Section 3 provide us with an insight on how the system might behave. Since in theory, the component model parameters can be selected arbitrarily, our insight is limited until we specify the exact components and parameterize the model accordingly.

4.1 Example component models

Table 1 lists three commercial UPS models with efficiency data provided by Carbontrust [4]. Based on the four efficiency points, normalized power losses for each point can be calculated. Quadratic curve can then be fitted to the four points to get the three model coefficients. Calculated model coefficients are also presented in the table together with the typical 'goodness-of-fit' indicator R-square. For the R-square, a value of one indicates a perfect fit between the fitted model and data. Hence, the coefficients in Table 1 provide very accurate presentations of the underlying models, as indicated by the high R-square values.

We also need to specify the UPS peak power design parameter. Since this parameter can also be freely selected, we could end up with under- or over-provisioning of the UPS system relative to the rest of the system. It is a reasonable starting point to look for the optimal sizing, since skewed provisioning of any component will lead to under- or over-provisioning of other components. Our UPS peak power is obviously tied to the rest of the system. For optimal system, UPS will reach 100 % load conditions simultaneously with other components. At this point, we can calculate the normalized power loss for a given UPS unit by equation (2), by setting $L_{Load} = 1$. Normalized power loss is then the sum of the three coefficients. Applying this to to equation (1), we get the normalized relationship for UPS power flow. However, we need to specify other components as well, to acquire the UPS input or output power. It should be noted that we could have calculated the full load power loss directly from the efficiency data, but this may present discrepancy if the fitted quadratic model does not provide perfect fit to the efficiency data. The approach taken here should provide better consistency.

Acquiring models for the cooling system is more difficult, due to the large number of solutions and operating conditions. Fully developed polynomial ensemble models or benchmarks are not readily available. Since the focus of our paper is to study the system-level power flow, we will utilize a straightforward model that captures the characteristics of chiller and fan performance.

We use a normalized cubic model for the chiller, defined by the equation

$$P_{Ci,Chiller} = 0.015Q_{\%}^3 - 0.02Q_{\%}^2 + 0.2Q_{\%} + 0.015 \quad (20)$$

This results in a COP curve typical for chiller, defined by

$$COP = \frac{Q_{\%}}{0.015Q_{\%}^3 - 0.02Q_{\%}^2 + 0.2Q_{\%} + 0.015} \quad (21)$$

This characterizes a typical chiller behavior as presented, for example, in [2].

For the fan model we will use a benchmark provided in [1]:

$$P_{Ci,Fan} = 0.025Q_{\%}^3 - 0.01Q_{\%}^2 + 0.1Q_{\%} + 0.001 \quad (22)$$

We acquire our cooling ensemble model by summing equation (20) and (22), resulting

$$P_{Ci} = 0.075Q_{\%}^3 - 0.03Q_{\%}^2 + 0.3Q_{\%} + 0.016 \quad (23)$$

Table 1: Efficiency and model coefficient data for commercial UPS units. Efficiency data is provided by [4].

		Efficiency @ load%				Model coefficients			
UPS	Peak Power	25	50	75	100	k_0	k_1	k_2	R-square
UPS #1	600kVA	93.93	96.23	96.92	97.03	0.01482	0.002332	0.01337	0.9987
UPS #2	600kVA	95.6	96.3	96.0	95.6	0.006937	0.01089	0.02828	0.9998
UPS #3	600kVA	95.2	95.6	95.7	95.5	0.004318	0.03062	0.01206	0.9995

Dimensioning of the cooling is similar to the UPS. Optimal provisioning is reached when the cooling system is capable of handling the peak total input power.

4.2 Comparison of topological efficiency

One of the interesting possibilities provided by the system-level simulation models is the ability to compare different topologies for a given set of equipment. There are several ways to formulate the problem, but since we are interested in the relative difference between topologies, we can present the difference in server input powers as a function of total input power. Let us compare the two cases A and C, which allows us to evaluate the cost of UPS backed cooling.

Since we can use normalized values, let us assume that the total input power varies from 0 to 1. Therefore, if we seek optimal provisioning, our cooling design can be set $Q_{Cd} = 1$ as we assume that all the power is transformed into heat. Furthermore, we can also calculate the P_{Ud} for the Case A, since we now know that the peak input power of the UPS is 1.

Since the UPS efficiency is defined as

$$\eta_{peak} = \frac{P_{Uo}}{P_{Ui}} = \frac{P_{Ui} - P_{Ul}}{P_{Ui}} = \frac{P_{Uo}}{P_{Uo} + P_{Ul}} \tag{24}$$

and since our UPS model coefficients are determined for normalized output power, we can set $L_{Load} = 1$ in equation (2) resulting in

$$P_{Ud,A} = \frac{1}{1 + P_{Ul}} = \frac{1}{1 + K_0 + K_1 + K_2} \tag{25}$$

For Case C, we would have to know the cooling power consumption to know how much of the total power goes through the UPS. At peak load, the normalized cooling consumption is given by the equation (7). Since we have defined $Q_{Cd} = 1$, the peak UPS input power is simply

$$P_{Ui} = 1 - N_0 - N_1 - N_2 - N_3, \tag{26}$$

Consequently, UPS design peak output power for the topology in Case C can then be calculated as

$$P_{Ud,C} = P_{Ui}\eta_{peak} = \frac{1 - N_0 - N_1 - N_2 - N_3}{1 + K_0 + K_1 + K_2}, \tag{27}$$

Equations (25) and (27) therefore provide us with the fundamental difference between the dimensioning of the UPS for the cases A and C.

We can substitute $Q_{Cd} = 1$ and equations (25) and (27) into equations (28) and (30) in Appendix A to acquire simplified relationship between server input and total input power for cases A and C, respectively. Resulting lengthy equations are included in Appendix A as equations (31) and (32). These depict the power relationship as a function of only the model coefficients, hence allowing us to experiment with different efficiency models. Solving the roots of equations (31) and (32) gives us the base power consumption of the auxiliary equipment, that is, the power consumed when the server input power is zero.

By substituting model coefficient data, we can plot the behavior of the two systems. Let us use the UPS model #1 and the cooling model presented in equation (23). The resulting power curves are shown in Fig. 3. These curves display the small, but observable difference in the available server power between a system with a UPS backed cooling and one without. Difference in the curves also highlights the higher peak efficiency and the lower idle consumption in systems without UPS backed cooling. We can also examine

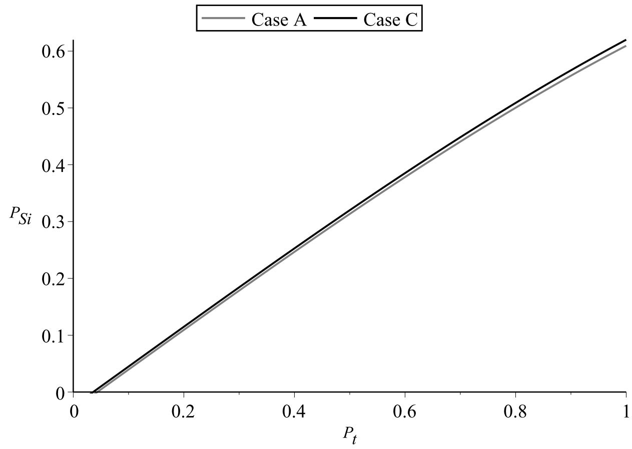

Figure 3: Server input power as a function of total system power for the topologies in cases A and C.

the ratio of server input power for the two topologies. The ratio is plotted in Fig. 4, and highlights the relative difference in efficiency for the two topologies.

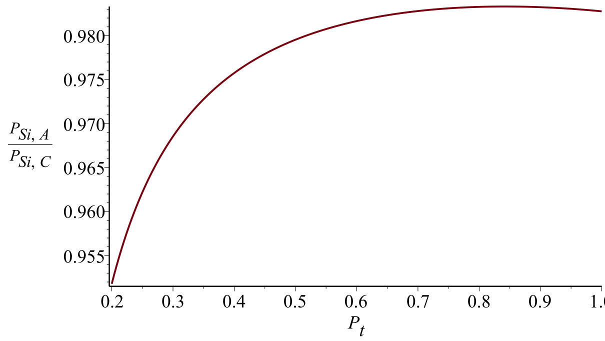

Figure 4: Ratio of the server input powers for the topologies in cases A and C, as a function of total system power.

4.3 Effects of UPS model efficiency

Another interesting aspect in data center modeling is the comparison of different component models and their effect on the overall efficiency. While it is trivial to compare, for example, the efficiency of different UPS units, the impact of different models to the overall efficiency is clearly more complex. The presented system level models, however, allow us to easily compare the impact of different component models and also their different combinations. To exemplify this, we compare the difference in the available server power for the various UPS units presented in Table 1. Figure 5 presents the difference between UPS units of UPS #1 and UPS #2 for the topologies in cases A and C. The curves are acquired by substituting UPS coefficients from Table 1 and the cooling model data from equation (23) to the equations (31) and (32) for each unit and plotting the difference of the two results.

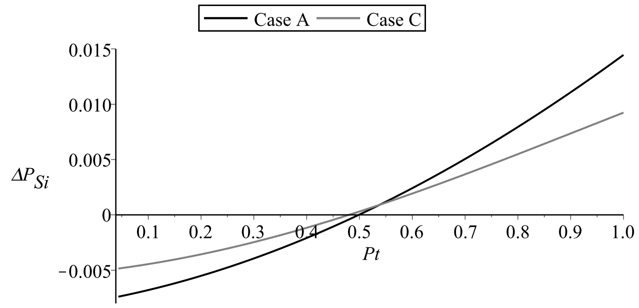

Figure 5: Difference between UPS #1 and UPS #2 in terms of available server input power. Results are calculated for both case A and C topologies and plotted as a function of total system power.

The difference between UPS #1 and UPS #3 is depicted in Fig. 6.

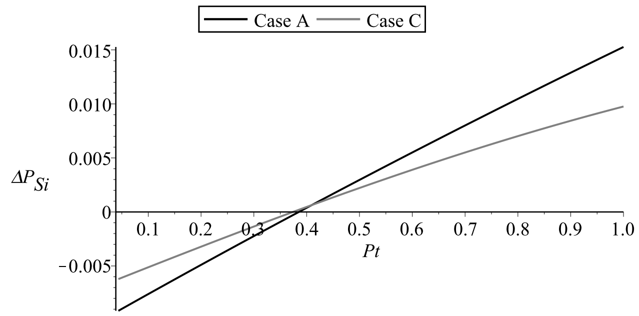

Figure 6: Difference in server input power for the comparison of UPS #1 and UPS #3.

Figures 5 and 6 clearly show the impact of UPS #1's better efficiency at high load levels to the overall system efficiency. Furthermore, these figures also show that the UPS efficiency has a higher impact in systems conforming to Case A topology. However, a more obscure result can be observed in the load level at which the UPS #1 becomes the more efficient one. There is a small, but observable difference for the A and C topologies at the load level when the UPS units are equal. Differences for the cases in Figures 5 and 6 are 0.018 and 0.011, respectively.

4.4 Evaluating cost of over-provisioning

The separation of the provisional scaling and the characteristic component efficiency in the presented models provide certain interesting modeling possibilities. One practical question of interest is the effect of over-provisioning on the efficiency. To observe the behavior of the available server input power with various levels of component over-provisioning, we can substitute model coefficients of interest in equation (28), while leaving P_{Cd} and P_{Ud} as changeable parameters. Figures 7 and 8 present the change in available server power as the over-provisioning of either the UPS or the cooling increases, while the other is kept at constant optimal provisioning level. The optimal level for the UPS is defined by equation (25), while the cooling provisioning level is the nominal total heat load $Q_t = Q_{Cd} = 1$. The results are plotted over a subset of total input power to also depict the effect of power level. The two figures present a system with UPS #1 from Table 1 and cooling system model of equation (23) applied to Case A by equation (28).

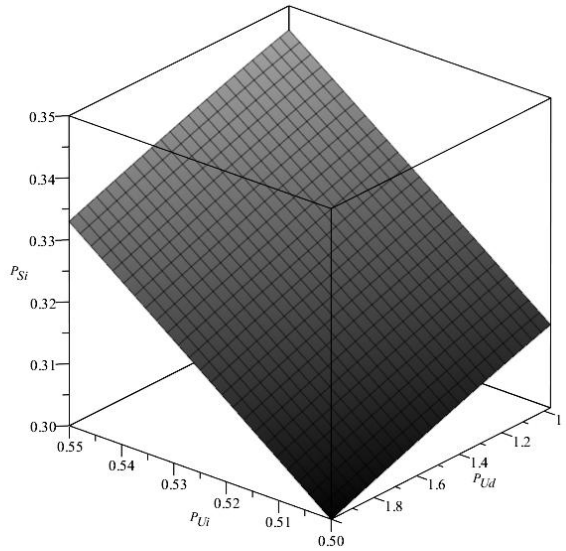

Figure 7: Available server input power as a function of total input power and UPS over-provisioning. Cooling is optimally provisioned and hence constant.

Figures 7 and 8 show observable decrease in the available server input power when component over-provisioning increases. While the effects between cooling and UPS over-provisioning are very similar, there are minute but distinctive differences in both amplitude and linearity of the effect. In this particular case, the over-provisioning of UPS unit seems to decrease the efficiency more, whereas the over-provisioning of the cooling side results a smaller, but less linear effect.

5. CONCLUSIONS

In this paper, we have shown that it is feasible to model overall data center efficiency by utilizing polynomial component models and capturing their interactions. While we have discussed a subset of all the possible system level variations, the results present the most fundamental cases and hence form a basis for more specific use cases and scenarios. These can be constructed by, for example, changing what constitutes to the heat load and how the components are interconnected. The presented models also provide a basis on which to construct complex multicomponent systems in which we have a larger number of individually controlled equipment. Furthermore, we could advance the solutions by including server power supply and CPU efficiencies to capture metrics de-

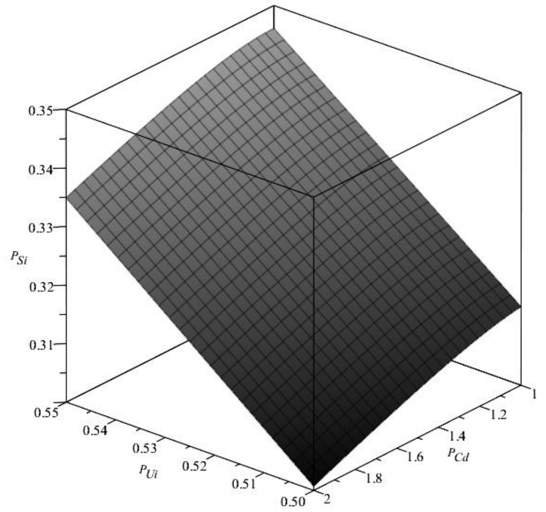

Figure 8: Available server input power as a function of total input power and cooling system over-provisioning. UPS is optimally provisioned and hence constant.

scribing, for example, the available processing capacity per total input power.

Hence, the approach presented here provides a general solution that is easily adopted, in part or in full, to various simulation and modeling tasks concerning other energy-aware aspects of IT. It also provides a fundamental basis for dissecting and understanding benchmark results.

In addition to the model construction, we have also presented three relevant use cases for the models, which show a number of interesting results for a data center environment. Simulating these type of cases allows us to compare both quantitative and qualitative aspects of possible efficiency improvements.

While some of the results and aspects presented in this paper could be achieved via iterative calculations and procedural simulations in general, it should be noted, that our analytical models make it possible to construct exact and computationally light equations for various simulation tasks and comparisons of interest.

The overall accuracy of the presented solutions and simulations obviously depends on the component model accuracies. A general problem lies in the fact that efficiency data provided by manufacturers is often inaccurate, especially at low load levels. This presents some ambiguity on how the components behave at, for example, zero load. However, when needed, the component models could be improved by benchmarking actual equipment in real setups.

Second and third order polynomials, as used in this paper, capture the fundamental physical characteristics of the components. However, the required polynomial order for a given accuracy is not necessarily easy to determine. It is possible that in some cases, the order of the polynomials would need to be significantly higher for adequate accuracy. Fortunately, our approach allows us to scale the polynomial model order freely, thus allowing us to attain the required accuracy. Our approach consequently provides a two-folded solution; it allows the use of precise models when needed, but also rough approximations when accurate models are unavailable. This is important, since simulating new solutions before they exist physically is of great practical interest.

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APPENDIX

A. EQUATIONS FOR SERVER INPUT POWER

Equations (28), (29) and (30) present server input power as a function of total system input power, with model coefficients as parameters, for the three topologies presented in cases A, B and C, respectively
Equations (31) and (32) present the relationship for cases with optimal component provisioning.

Case A

$$P_{Si} = \frac{1}{2K_2Q_{Cd}^4}(-2K_2N_1Q_{Cd}^4P_{Ui} - 2K_2N_2Q_{Cd}^3P_{Ui}^2 - 2K_2N_3Q_{Cd}^2P_{Ui}^3 - 2K_2N_0Q_{Cd}^5 - K_1Q_{Cd}^4P_{Ud} - Q_{Cd}^4P_{Ud} + \left[4K_2Q_{Cd}^8P_{Ud}P_{Ui} + K_1^2Q_{Cd}^8P_{Ud}^2 + 2K_1Q_{Cd}^8P_{Ud}^2 - 4K_0K_2Q_{Cd}^8P_{Ud}^2 + Q_{Cd}^8P_{Ud}^2\right]^{1/2}) \tag{28}$$

Case B

$$P_{Si} = \frac{1}{2K_2Q_{Cd}^4P_{U2d}}([(K_1Q_{Cd}^4P_{U2d}P_{Ud} + Q_{Cd}^4P_{U2d}P_{Ud})^2 - 4K_2Q_{Cd}^4P_{U2d}(k_1N_1Q_{Cd}^4P_tP_{U2d}P_{Ud} + k_1N_2Q_{Cd}^3P_t^2P_{U2d}P_{Ud} + k_1N_3Q_{Cd}^2P_t^3P_{U2d}P_{Ud} + 2k_2N_0N_1Q_{Cd}^5P_tP_{Ud} + k_2N_1^2Q_{Cd}^4P_t^2P_{Ud} + 2k_2N_0N_2Q_{Cd}^4P_t^2P_{Ud} + 2k_2N_1N_2Q_{Cd}^3P_t^3P_{Ud} + 2k_2N_0N_3Q_{Cd}^3P_t^3P_{Ud} + k_2N_2^2Q_{Cd}^2P_t^4P_{Ud} + 2k_2N_1N_3Q_{Cd}^2P_t^4P_{Ud} + 2k_2N_2N_3Q_{Cd}P_t^5P_{Ud} + k_1N_0Q_{Cd}^5P_{U2d}P_{Ud} + k_2N_0^2Q_{Cd}^6P_{Ud} + k_0Q_{Cd}^4P_{U2d}^2P_{Ud} + K_0Q_{Cd}^4P_{U2d}P_{Ud}^2 + N_1Q_{Cd}^4P_tP_{U2d}P_{Ud} + N_2Q_{Cd}^3P_t^2P_{U2d}P_{Ud} + N_3Q_{Cd}^2P_t^3P_{U2d}P_{Ud} + N_0Q_{Cd}^5P_{U2d}P_{Ud} - Q_{Cd}^4P_tP_{U2d}P_{Ud} + k_2N_3^2P_t^6P_{Ud})]^{1/2} - K_1Q_{Cd}^4P_{U2d}P_{Ud} - Q_{Cd}^4P_{U2d}P_{Ud}) \tag{29}$$

Case C

$$P_{Si} = \frac{1}{2K_2Q_{Cd}^2}([(K_1Q_{Cd}^2P_{Ud} + Q_{Cd}^2P_{Ud})^2 - 4K_2Q_{Cd}^2(K_0Q_{Cd}^2P_{Ud}^2 + N_1Q_{Cd}^2P_tP_{Ud} + N_2Q_{Cd}P_t^2P_{Ud} + N_0Q_{Cd}^3P_{Ud} - Q_{Cd}^2P_tP_{Ud} + N_3P_t^3P_{Ud})]^{1/2} - K_1Q_{Cd}^2P_{Ud} - Q_{Cd}^2P_{Ud}) \tag{30}$$

Case A, Optimal provisioning

$$P_{Si} = -\frac{2K_2P_t\left(P_t\left(N_3P_t + N_2\right) + N_1\right) + 2K_2N_0 - \sqrt{\frac{4K_2P_t + \frac{K_1^2+2K_1-4K_0K_2+1}{K_0+K_1+K_2+1}}{K_0+K_1+K_2+1}} + \frac{K_1}{K_0+K_1+K_2+1} + \frac{1}{K_0+K_1+K_2+1}}{2K_2} \tag{31}$$

Case C, Optimal provisioning

$$P_{Si} = \frac{\sqrt{\frac{(-N_0-N_1-N_2-N_3+1)\left(-4K_2\left(-\frac{K_0(N_0+N_1+N_2+N_3-1)}{K_0+K_1+K_2+1} + P_t(P_t(N_3P_t+N_2)+N_1-1)+N_0\right) - \frac{(K_1+1)^2(N_0+N_1+N_2+N_3-1)}{K_0+K_1+K_2+1}\right)}{K_0+K_1+K_2+1}}}{2K_2} + \frac{\frac{(K_1+1)(N_0+N_1+N_2+N_3-1)}{K_0+K_1+K_2+1}}{2K_2} \tag{32}$$