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# Model-based Approach to Data Center Design and Power Usage Effectiveness Assessment

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**Abstract**

Data Centers (DC) are complex systems, which provide an environment to host Information and Technologies (IT) equipment. DCs are typically composed of a variety of components including servers, storage systems, networking infrastructures in addition to non-IT equipment such as power distribution and cooling systems. In order for a DC to function properly, all of its components need to be correctly configured and integrated. However, the variety of configurations and the interdependencies of DC sub-systems create challenges in understanding and optimizing DC complexities. In this paper, we present a system modeling approach, which supports the design of DCs and a quantitative assessment of their energy efficiency. This modeling approach aims at controlling the design complexity of DC infrastructure and ensuring the consistency of such designs. The cornerstone of our approach is a generic DC metamodel (DCMM), which captures the DCs heterogeneous structure, main characteristics, and diverse constraints. Furthermore, we propose a method to generate a Power Flow Model (PFM) from an input DC model. The PFM is then used to compute the DC Power Usage Effectiveness (PUE) metric. We evaluate the applicability of our approach through a use case of the Consortium Laval-UQAM-McGill and Eastern Quebec (CLUMEQ) data center.



*Keywords:* UML, Data center, Metamodel, generation algorithm, Power flow model, PUE ;

## 1. Introduction

The applications and technologies enabled by the various concepts and paradigms of cloud computing, mobile computing and Internet of Things, and their combination, have led to growing volumes of data to process, store, and exchange. This in turns led to a growing need for data centers (DC). Google, Amazon, Microsoft, Facebook, and IBM are constantly building new DCs to store and process huge volumes of data. According to [2], DC sector is growing rapidly and the industry is expected to have an annual growth rate of over 10 percent until 2019.

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The design of a DC is a challenging engineering task because of several factors. First, a DC is a complex system of systems due to its various IT and non-IT sub-systems interactions and dependencies. Second, diverse constraints, for instance environment-related (e.g., humidity and temperature), location-related, and system function related, should be satisfied when designing a DC. Third, a DC design should also satisfy several requirements in terms of availability, security, and efficiency.

DCs being large scale computing infrastructures, consume typically significant energy budgets. Consequently, they are subject to energy efficiency requirements. The efficiency of DCs is typically measured by the Power Usage Effectiveness (PUE) metric, which is the amount of energy at the entrance divided by the energy consumed to run the IT infrastructure. The closest PUE to 1 indicates an optimal energy efficiency. Indeed, a PUE of 1.0 means that all energy is used by computers while a PUE of 2.0 means that for every watt of power used in IT, one watt is used for cooling and to power auxiliary equipment and also accounts for power losses in the system.

In this paper, we focus on addressing the issue of DC architecture design complexity through a modeling approach, which enables the assessment of the power usage effectiveness. To this end, we propose a generic data center metamodel (DCMM), which defines the abstractions to capture the structure of the physical infrastructure of DCs with their interdependencies, constraints and relevant requirements. This metamodel can serve as a basis to define a domain specific language (DSL) to support the different stakeholders in the DCs design, deployment, operation and management. In particular, we propose in this paper a method which uses the DCMM to generate the Power Flow Model (PFM). The PFM is a specific model which captures all the parameters required to calculate the PUE metric in the assessment of the energy efficiency of a data center. We illustrate our proposed approach using the CLUMEQ data center case study.

The remainder of our paper is organized as follows. Section 2 introduces the relevant related works. In Section 3, we describe and discuss the proposed data center metamodel. In section 4, we present our method to generate the Power Flow model (PFM) using the DCMM. Section 5 is devoted to illustrate our approach by using a real DC scenario. The conclusion is presented in Section 6.

## 2. Related Works

DC is an environment designed to host IT equipment on the top of a solid infrastructure (power systems, cooling systems and control systems). The actual implementation of a DC is more complex than already described in literature works. DC are composed of three main infrastructures: IT, cooling and power.

To function properly, a DC must also have an adequate infrastructure: a power distribution system, an electricity grid, energy reserves, generators dedicated to backup, a ventilation and cooling system, and a powerful Internet connection. Such an infrastructure requires sufficient and secure physical space [5, 15].

In literature review, there are many works that define and present the DC infrastructure. But, each work takes each part of the DC in one point of view. In addition, DCs have often their design hidden from the public domain which creates more challenges.

To address the DC design issues, Snevely and Avgerinou et al. define the power distribution concepts and design in [13, 1]. Those works are a guideline that should be taken into consideration during the DC design. But they present only one DC case, which cannot be generalized. In another point of view for the DC design, Schreiber, Pierson et al. and Slessman et al. describe the modular approaches in [11, 6, 12] in order to help business leaders and IT managers build a business case for a replacement or a modernization of their DC design. It was the first proposition of IBM to make the DC modular. In the same context, Schreiber presents in [11] the DC modularity advantages. This modularity is one of our DCMM requirements in order to illustrate the utility of the proposed metamodel. For the data center modeling, we can find the work presented by Ponsard,Guerout et al. and Ponsard et al. where they propose in [7, 4, 8] a UML model. The proposed model presents a UML profile for the energy-aware design of cloud application. The UML presentation simplifies the application level view and helps to define the energy consumption and measurements for Cloud services. In another point of view, Sondur et al. define an UML-based model in [14] to design the data center network by proposing a holistic model for energy management of the DC networks. They use NS3 (Network simulator) to improve their results. Also, Rygielski defines in [10] a metamodel for the performance modeling of network infrastructures in modern data centers. Each proposed sub-metamodel presents respectively DC network configuration, traffic and structure.

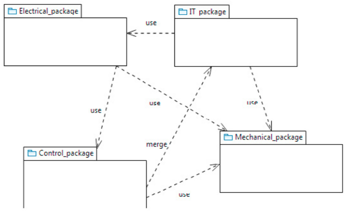


Fig. 1. DCMM packages structures.

Our work is different from the related works in that it presents a generic DCMM for DC by describing the different systems and the main constraints. To the best of our knowledge, none of them has presented yet the DC systems interactions and interdependencies.

## 3. Data Center MetaModel

### *3.1. Metamodel Structure Overview*

The proposed DCMM presents an abstract view of the different sub-systems composing a DC, namely, the electrical, mechanical, IT and Control sub-systems. Therefore, the overall structure of the DCMM, shown in the UML package diagram in Figure 1, is composed of 4 packages (i.e. electrical package, mechanical package, IT package and control package). Each package presents a DC space (IT space, mechanical space, electrical space and control space).

There is a multi-relations between the DCMM packages as shown in Figure 1. At some level, there is an interdependencies between some classes of each package. For example, the relation between the IT package and mechanical package is a ”usage” relation where some classes of the mechanical package are used by the IT classes. For more detail, a DC may generally contain a set of IT equipment arranged in IT racks. Those equipment are classes of the IT package. Moreover, those equipment generate heats so DC need to be cooled using cooling units, such as computer room air conditioners (CRAC) for efficient thermal management (the CRAC is a class of the Mechanical package).

### *3.2. Metamodel requirements*

We discuss in this section the main three requirements defined for the proposed DCMM metamodel. The DCMM metamodel should (1) be extensible, (2) be modular and (3) Define DC power flows. There are many others but in this paper, we only describe three of them.

- $RQ_1$ : DCMM Extensibility
  The DC architecture designers can use the DCMM metamodel through a specific DSL in order to specify DC design model. There is a need for such design models to be flexible and scalable considering the technology continuous change.
- $RQ_2$ : DCMM modularity
  The proposed DCMM metamodel enables creating smaller building blocks that are easier to manage. With space modeling, designers will get an idea of the modules that can exist in each part of the DC as well as the modules that connect together.
- $RQ_3$ : DCMM defines power flows in a data center
  We can characterize the systems defining energy flows, ranging from electrical systems, and mechanical systems to arrive at IT systems. This goal brings us to define Power Flow Model (PFM). It is a generation from a DCMM to improve energy efficiency analysis.

### *3.3. Metamodel Constraints*

We have identified several constraints in the definition of the DCMM metamodel. These constraints are divided into 4 classes: DC location, power voltage transformation, temperature constraint and DC and server lifespan [3]. In the following, we discuss only a subset of constraints at different levels.

- $C_1$ : Power constraints : (i) The input utility power high voltage should be converted to a low voltage.And (ii) When the utility power is down, the UPS takes the backup (by providing backup power) within a period of the time between 10 to 20 seconds. And the ATS invokes UPS, transfers power supply from its primary source to a backup source.
- $C_2$ : Location constraints: **If** DC is located in Europe, Asia, South America **then** utility input power can be 480 V AC or 600V AC **and** PDU output power after conversion is 208/120V AC **else** PDU output power is 400/230V AC.
- $C_3$ : DC and server lifespan [9]: (i) The maximum DC physical infrastructure lifespan is 20 years (e.g. a Canadian DC lifespan is 13 years).(ii) DC server lifespan is between 3 to 5 years.
- $C_4$ : Temperature constraints: a DC ambient temperature range should be between 21 °C to 23 °C. This is the optimal settings for system reliability.

### *3.4. DCMM electrical package*

In this section, we focus on the DCMM electrical package. This is a key part of the Metamodel which is used in driving the generation of the PFM model as will be detailed in the next section. The UML model of the concepts in this package along with their relationships and constraints is shown in Figure 2. The main classes of this model are as follows:

***Input-power class:*** This class presents the main DC power supply. This is the superclass of two classes that inherit, namely the Input_Utility_Power class (i.e. electrical power) and the Alternate Power class that presents the renewable energy sources (e.g. hydroelectric, wind,solar power, etc.).

The input utility-power is generally having a high-voltage. This requires therefore to use an input transformer system. Consequently, the Input-power class have a directed association to one Input-transformer class.

***Input-transformer class:*** This abstracts the system which transforms high voltage AC power to medium or low voltage AC power. This transformation is required to comply with the power constraint defined previously ($C_1$).

***Switchgear and Switchboard classes:*** These classes abstract the Switchgear and Switchboard systems, which are used to manage the input-power system operation modes. Those classes have an association relationship with the TS (Transfer Switch) class. For Switchgear and Switchboard systems, there is notable differences in configurations, components, standards, applications, reliability, and selection criteria between these two types of power distribution equipment. The main switchboard is directly connected to a transfer switch system. The choice of using either switchgear or switchboard must be based on the design of the power system.

***TS class:*** The Transfer switch class is used to increase the system Mean Time Between Failures (MTBF) through redundancy of supplies using the generator sub-system. There are mainly two classes which inherit from the TS class: STS (Static Transfer Switch) and ATS (Automatic Transfer Switch) class. The TS class has one or many direct association with the UPS class.

***UPS class:*** The UPS class abstracts the sub-system that allows the DC power system to continue operating for at least a short time when the primary utility-power source is down.

**DCMM OCL constraints**

The constraints of the metamodel discussed earlier are often captured in the structure of the metamodel (e.g. relationships between classes such as the association between the Input-Power and Input-Transformer, multiplicities, etc.). Some constraints need to be specified more formally and can be expressed using the Object Constraint Language (OCL).

For instance, the power constraint ($C_1$) is specified in OCL as bellow:

**context** Utility-power::Transform-voltage(voltage : int)
**pre** : voltage = high
**post** : voltage = voltage@pre +transform

This constraint is mainly used to ensure that the high voltage entered to supply the DC should be transformed to a low voltage in order to supply the the IT equipment.

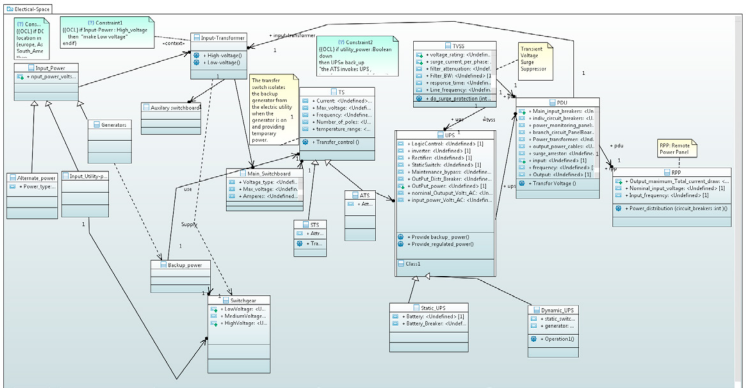

Fig. 2. DCMM electrical package.

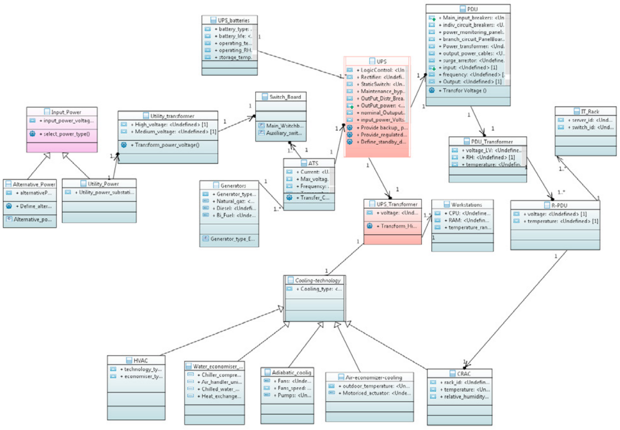

Fig. 3. powerFlow model

## 4. Generation of power flow model

The energy consumption issue is exacerbated with the high demand for cooling in the DCs. In addition, the electrical equipment in a DC such as the Uninterruptible Power Supplies (UPS), Power Distribution Units (PDUs) and transformers, have an impact on PUE values. In this context, there is a need for a methodology to improve the accuracy of the PUE metric in assessing the power usage efficiency in DCs. In this paper, we present a methodology which leverages our DCMM metamodel to generate automatically the power flow model. This model reflects the parameters and information relevant in the definition of the PUE metric. In this section, we define the PFM and detail the rules and steps to generate the PFM and how we compute the PUE metric using this model. Our ultimate goal is to support the DCs energy efficiency. This requires optimization models which involve a variety of parameters and constraints that are difficult to identify and extract from complex systems such as a DC with many sub-systems inter-dependencies and interactions. Therefore, there is a need for a model, which abstracts further the DCMM metamodel to capture only the subsystems relevant for the power flow in a DC and their parameters. We call this model, the power flow model (PFM).

### *4.1. Power Flow Model*

The power flow model as shown in Figure 3 includes the utility power, generators, UPS, PDU and IT-rack classes from the electrical package of the DCMM metamodel; the Water-Economizer-Cooling, Adiabatic cooling,

**Algorithm 1:** Generation algorithm for PFM

**Input : M instance of DCMM**
**Output : pf instance of PFM**
**begin**
Step 1 : Create pf :: Coolingpkg ; Create pf :: Powerpkg; Create pf :: ITpkg;
Step 2: For each $e$ ∈dcm :: Mechpkg GenerationRule (e);
Step 3: For each $e$ ∈dcm :: ITpkg GenerationRule (e);
Step 4: For each $e$ ∈dcm :: electricalpkg GenerationRule (e);

Air-economizer-cooling, HVAC and CRAC classes from the mechanical package; and the IT-Rack from the IT package. The power flow model captures the following interaction between the aforementioned clases. The input power to a DC via a utility Power presents the main power source. DCs also use a generator that serves as a back-up power source during a utility failure. An automatic transfer switch is used to automatically select and switch between these two sources. When the ATS attempts to switch to the generator power supply, it takes 10 to 20 seconds for the to be enabled before power can be supplied [14]. Meanwhile, the UPS is used to bridge this time gap between the power failure of the utility and the activation of the generators. UPS stores power using batteries that typically have a run time of 20 minutes to power the DC during this transition [2]. Then, PDU supplies the multi-racks which host the IT equipment.

### *4.2. PFM generation algorithm*

Our approach to compute the PUE metric using the PFM model requires the generation of an instance of the PFM model from DCMM instance model of a particular data center. The general procedure of this generation is specified with the following Algorithm 1.

**Notation** In the following, we use this basic notation:

- Model::Package::Modelelement.
- Package::Modelelement.

**Generation Rules** The generation algorithm is based on the following main mapping rules:

- $GR_1$ : An DCMM-electricalPackage is mapped into a PFM-power classes.
- $GR_2$ : An DCMM-ITPackage is mapped into a PFM-IT classes. but we should stop only on the IT-rack class of the MM-ITpackage.
- $GR_3$ : An DCMM-mechPackage is mapped into a PFM-cooling classes.

## 5. CLUMEQ case study

In this section, we present the details of a case study based on the CLUMEQ DC in order to illustrate the DCMM metamodel and our proposed method to assess the PUE metric. To this end, We discuss the instantiation of the DCMM for this DC, generate the corresponding PFM model and evaluate the PFM- based PUE for this DC.

### *5.1. CLUMEQ data center*

CLUMEQ (Consortium Laval-UQAM-McGill and Eastern Quebec) is a Canadian High Performance Computing consortium led by McGill University in Montreal, Quebec. The CLUMEQ DC is used in this work to instantiate our proposed DCMM and help in the validation process of this metamodel. In The following table we present the main CLUMEQ design architecture and data.

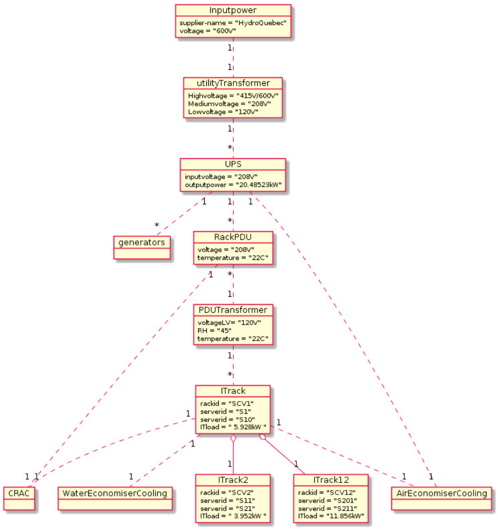


Fig. 4. CLUMEQ power flow model.

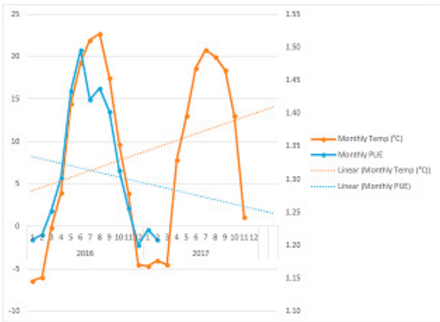

Fig. 5. The effect of temperature on the energy efficiency of a data center.

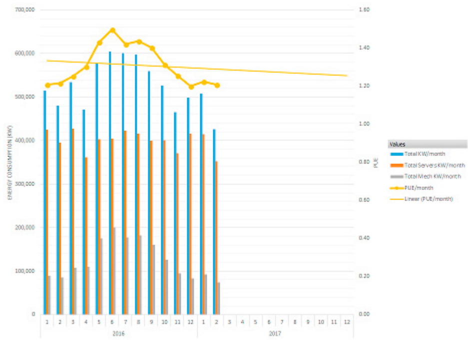

Fig. 6. CLUMEQ energy consumption and PUE

## 5.2. CLUMEQ DCMM instance

The CLUMEQ DC design mainly two parts: part 1 where IT equipment are placed on the UPS-based rack (rack SCV16 and SCV14) in order to use it for data backup and part 2 where IT equipment are not part of the UPS-based system (racks SCV2 to SCV12). Moreover, the CLUMEQ DC uses 3 systems of cooling (air-side cooling, water cooling and CRAC cooling system ).

## 5.3. CLUMEQ Power Flow Model and PUE Evaluation

The power flow model corresponding to CLUMEQ DCMM instance generated by following the generation rule algorithm presented earlier is shown in Figure 4.

In order to validate our PFM-based approach to compute the PUE, we use the CLUMEQ real data to calculate the annual PUE values respectively for 2016 and 2017. In particular, we considered the the effect of the temperature constraint ($C_5$) on the PUE variations. The results are shown in Figure 5.

As the CLUMEQ DC uses the free cooling technology as one of cooling technology to cool the whole data center. So, the decrease in temperature makes it possible to substantially extend the periods during which it is not necessary to use the heat pump to cool the DC. In this case, the cooling load will be decreased which explains the

PUE values variation between 1.2 and 1.3. Those values are calculated during the cold period of the year (December, January, February). Otherwise, for the rest of the year, the free Cooling technology is not used. In this case, we acknowledge that the PUE is increased from 1.3 to 1.5. Based on this information, we evaluate the effect of the temperature on power usage effectiveness (PUE) metric. As a result, DCs are among the most complex and energy-intensive environments due to high internal loads, low temperature, and humidity settings, and continuous operation. Based on the PUE formulation which is calculated by dividing the total energy consumption (energy consumed by IT equipment, mechanical equipment, electrical equipment) and the IT energy consumption. So, in Figure 6, we present the PUE in function of the energy consumed respectively by the IT equipment where we focus more on the servers consumption and the mechanical equipment consumption.

## 6. Conclusion and Future works

The need for data centers is continuously growing due diverse applications of cloud computing, mobile Computing and IoT for instance. They are also becoming more complex to design, deploy and operate. We have presented in this paper a system modeling approach, which supports the design of DCs and a helps in the assessment of their energy efficiency. This modeling approach aims at controlling the design complexity of DC infrastructure and ensuring the consistency of such designs. The main specific contributions discussed in this paper are a metamodel for the data centers design architecture called (DCMM). This metamodel captures the DCs heterogeneous structure, main characteristics, and diverse constraints. Furthermore, we propose a method to generate a Power Flow Model (PFM) from an input instance of the DCMM. The PFM is then used to compute the DC Power Usage Effectiveness (PUE) metric. We evaluate the applicability of our approach through a use case of the CLUMEQ data center.
As future work, we plan to automate the DC design process by automatically generate DC models. Then, automatically, and intelligently predict the energy efficiency (EE) of each specific DC model.

## Acknowledgements

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