Models for Dependability and Sustainability Analysis of Data Center Cooling Architectures

Gustavo Callou*†, Paulo Maciel*, Dietmar Tutsch† and Julian Araújo*
*Informatics Center, Federal University of Pernambuco - Recife, Brazil. Email: {grac,prmm,cjma}@cin.ufpe.br
†Automation/Computer Science, University of Wuppertal - Wuppertal, Germany. Email: {g.callou,tutsch}@uni-wuppertal.de

***Abstract*—The advent of cloud computing, social networks and e-commerce have demanded more computational resources from data centers. Prominent issues are sustainability, cost and dependability, which are significantly impacted by the redundant infrastructures needed to support those services. In this context, models are important to support data center designers to estimate previous issues before implementing the final architecture. This paper proposes a set of models for the integrated quantification of sustainability impact, cost and dependability of data center cooling infrastructures with the support of an environment, namely, ASTRO. Besides, a model is proposed for verifying if the energy flow does not exceed the maximum energy capacity that each component can provide (considering power devices) or the maximum cooling capacity (assuming cooling equipment). Additionally, this work presents a case study which analyzes the environmental impact, dependability metrics as well as the acquisition and operational costs of five real-world data center cooling architectures.**

***Keywords*-Petri nets; RBD; EFM; Dependability Evaluation; Sustainability; Data Centers;**

I. Introduction

Environmental impacts have received great attention by scientific community and industries due to diverse concerns: the climate change, pollution and environmental degradation. In information technology (IT) systems, the emergence of paradigms, such as cloud computing and social networks, has demanded data center infrastructures with several computers. Indeed, data centers consume about 2% of the U.S. power generation [1], and, so, they also significantly contribute to a negative impact on the environment.

A widely adopted design principle in fault-tolerance is to introduce redundancy to enhance availability. However, since redundancy leads to additional utilization of resources, it is expected to have a negative impact on sustainability. In this context, designers need to verify several trade-offs and select the feasible solution considering sustainability impact, cost and dependability metrics. However, at present stage, data center designers do not have many mechanisms to support the integrated sustainability, cost and dependability evaluation of data center infrastructures. Indeed, two different data center architectures with similar availability levels and cost may have very different sustainability impact.

This work proposes a set of models for the integrated quantification of sustainability impact, cost and dependability of data center cooling infrastructures. The proposed approach takes into account a hybrid modeling strategy that considers the advantages of both stochastic Petri nets (SPN) [2] and reliability block diagrams (RBD) [3] to evaluate system dependability. Besides, a model is proposed for verifying if the energy flow does not exceed the maximum energy capacity that each component can provide (considering electrical devices) or the maximum cooling capacity (assuming cooling equipment).

The integrated environment, namely, ASTRO has been implemented to support the joint evaluation of sustainability, cost and dependability. In addition to Reliability Block Diagrams (RBD) and stochastic Petri nets (SPN) models, ASTRO provides data center sub-system modeling views (e.g., power and cooling data center views) which abstracts the utilization of RBD and SPN for non-specialized users.

Additionally, this work adopts reliability importance index (RI) [3] and proposes the RI with cost index (RCI) to create different data center architectures with higher availability. RCI is a prominent index to evaluate the necessity as well as the feasibility of redundancy in a system considering the acquisition cost of the devices.

This paper is organized as follows. Section II presents related works. Section III introduces basic concepts on data center infrastructures, dependability and sustainability. Section IV presents the sustainability, dependability and energetic models. Section V presents a real-world case study and Section VI concludes the paper.

II. Related Work

In the last few years, some works have been developed to perform reliability analysis of data center systems and a subset has also considered sustainability impact and cost issues.

Wei [4] combines the advances of both RBD and General SPN (GSPN) for quantifying availability and reliability of virtual data center (VDC). Data center cooling architectures are not the focus of their research and the proposed models are specific for modeling VDC.

Gmach [5] estimates the data center power usage based on the average CPU utilization across all servers. The paper

978-1-4673-2266-9/12/$31.00 ©2012 IEEE

does not provide any integrated comparison between the cost, sustainability impact and availability of data center architectures.

Chang [6] proposes a method for estimating the exergy consumption during the raw material extraction, manufacturing, operational, transport and disposal phases. Many assumptions are adopted to take into account the entire device lifecycle, which may turn the results far from reality.

III. Preliminaries

A. Data Center Infrastructure

In addition to the building facility, a generic data center system essentially consists of the following subsystems: (i) IT infrastructure; (ii) cooling infrastructure; and (iii) power infrastructure. This work focuses in the cooling infrastructures, which are basically comprised of computer room air conditioning (CRAC) units, chillers and cooling towers [7]. The cooling infrastructure may account around 40% of the total power consumption of the data center [8].

B. Dependability

The dependability of a system can be understood as the ability to deliver a set of services that can be justifiably trusted [3]. Indeed, dependability is related to disciplines such as fault tolerance and reliability. Reliability is the probability that the system will deliver a set of services for a given period of time, whereas a system is fault tolerant when it does not fail even when there are faulty components [9]. Availability is also another important concept, which quantifies the mixed effect of both failure and repair process in a system [3].

Reliability Importance (RI) is a metric that may be useful for identifying the most critical components. RI (or Birnbaum Importance) of a component *i* corresponds to the amount of improvement in system reliability, when the reliability of component i is increased by one unit [3]. The RI of component *i* can be computed as:

$$RI_i = R_s(1_i, \mathbf{p}^i) - R_s(0_i, \mathbf{p}^i) \quad (1)$$

in which RI_i is the reliability importance of component i; $\mathbf{p}^i$ represents the component reliability vector with the *i*th component removed; 0_i represents component *i* failure; and 1_i denotes the component *i* properly working.

Reliability and Cost Importance (RCI) is a metric that relates the previous RI considering the acquisition cost of components. The RCI of component *i* can be computed as:

$$RCI_i = RI_i \times (1 - \frac{C_i}{C_{sys}}) \quad (2)$$

in which RCI_i is the proposed reliability and cost importance index; RI_i is the reliability importance of component i; C_i is the acquisition cost of the component i and C_{sys} is the system acquisition cost.

C. Sustainability

This work quantifies the environmental impact in terms of the thermodynamic metric of exergy. Exergy is defined as the maximal fraction of the energy that could be theoretically converted in useful work [10]. The exergy contained in one kJ of oil is greater than the exergy contained in one kJ of water in the environment temperature. Oil can be used to move an automobile but water in the environment temperature cannot.

Although the exergy might be considered a better index for quantifying sustainability than simply the energy, its use must be made cautiously. For example, the exergy of the solar radiation is high, once it can be efficiently converted into useful work, however it causes very low environmental impact.

IV. Models

A. Energy Flow Model

This model represents the energy flow between the system components considering the respective efficiency and the maximum energy that each component can provide (considering electrical devices) or the maximum cooling capacity (assuming cooling devices).

The system under evaluation can be correctly arranged, in the sense that the required components are properly connected, but they may not be able to meet system demand for electrical energy or thermal load. For instance, consider the cooling infrastructure depicted in Figure 1 (a). Assuming the amount of heat that should be extract from the data center room corresponds to 10kJ (value associated to the source node S), and the maximum cooling capacity (Figure 1 (b)) of the intern nodes (i.e., components) CRACs and Chiller are 8kJ and 18kJ, respectively. Figure 1 (c) depicts a possible energetic flow, in which heat is extracted by both CRACs (with a load of 5 kJ in each component) and transferred to the Chiller (10 kJ). In another example, instead of adopting two CRACs, only one is considered. This system is depicted in Figure 1 (d) and it is able to extract 8kJ of heat (value associated to the target node T). Thus, the system is not able to cope with the required thermal load.

Figure 1 (e) depicts a system with 2 CRACs (CRAC1 and CRAC 2). The CRAC1 extracts three times more heat than the CRAC2. This system behavior is specified by weights on the edges of the graph. In this work, an Energy Flow Model is proposed to represent the heat transfer. This model is an acyclic, direct graph defined as follows.

$G = (N, A, w, f_d, f_c, f_p, f_\eta)$, where:

- $N = \{s, t, i \mid s \in N_s, t \in N_t, i \in N_i; N_s, N_t, N_i \subset N\}$ represents the set of nodes (i.e., the components), in which N_s is the set of source nodes, N_t is the set of target nodes and $N_i = N \setminus (N_s \cup N_t)$ represents the set of intern nodes, $N_s \cap N_i = N_s \cap N_t = N_i \cap N_s = N_i \cap N_t = \{\}$;

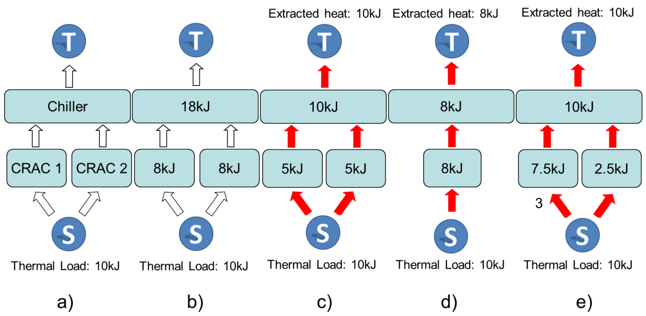

Figure 1. a) System example; b) Maximum Cooling Capacity; c) Successful Energetic Flow; d) Failed Energetic Flow; e) Representation with Weight.

- $A \subseteq (N_s \cup N_i) \times (N_i \cup N_t)$ denotes the set of edges (i.e., the component connections), $N \supseteq N' = \{(a,b)|a \in N_t, b \in N_s\} = \emptyset$, $N \supseteq N' = \{(a,a)\} = \emptyset$;
- $w : A \rightarrow \mathbf{R}^+$ is a function that assigns weights to the edges (the value assigned to the edge (j, k) is adopted for distributing the energy assigned to the node j to the node k according to the ratio $w(j,k) / \sum_{i \in j^\bullet} w(j,i)$, where $j^\bullet$ is the set of output nodes of j);
- $f_d : N \rightarrow \begin{cases} \mathbf{R}^+ & \text{if } n \in N_s \cup N_t, \\ 0 & otherwise; \end{cases}$
  is a function that assigns to each node the demanded heat to be extracted (considering cooling models) or the energy to be supplied (regarding power models);
- $f_c : N \rightarrow \begin{cases} 0 & \text{if } n \in N_s \cup N_t, \\ \mathbf{R}^+ & otherwise; \end{cases}$
  is a function that assigns each node with the respective maximum energy capacity;
- $f_p : N \rightarrow \begin{cases} 0 & \text{if } n \in N_s \cup N_t, \\ \mathbf{R}^+ & otherwise; \end{cases}$
  is a function that assigns each node (a node represents a component) with its retail price;
- $f_\eta : N \rightarrow \begin{cases} 1 & \text{if } n \in N_s \cup N_t, \\ 0 \leq k \leq 1, k \in \mathbf{R} & otherwise; \end{cases}$
  is a function that assigns each node with the energetic efficiency;

Due to the lack of space, this paper is not presenting the algorithm that traverses the graph checking if the demanded energy does not exceed the maximum energy capacity that each component can provide (considering electrical devices) or extract (assuming cooling devices).

Quantifying Cost

This work considers data center cost composed of acquisition and operational costs. The acquisition cost (AC) corresponds to the resources required (e.g., device retail prices) to implement the data center infrastructures. The operational cost (OC) is the cost to maintain the system in the operational mode which is represented by the following equation.

$$OC = E_{input} \times T \times E_{cost} \times A \quad (3)$$

where E_{input} is the electrical energy consumed; T is the assumed period; E_{cost} corresponds to the energy price; and A is the availability.

Similarly to the Energy Flow Algorithm, the algorithm that quantifies the cost is also not presented.

Quantifying Operational Exergy Consumption

This work computes the environmental impact in terms of the thermodynamic metric of exergy (also called available energy). The operational exergy consumption can be understood as the fraction of the heat dissipated by each equipment that cannot be theoretically converted into useful work. The following equation represents the system operational exergy.

$$Ex_{op} = \sum_{i=1}^{n} Ex_{op_i} \times T \times A \quad (4)$$

where Ex_{op_i} is the operational exergy of each device (Table I); T is the period of analysis; and A is the system availability.

Table I
OPERATIONAL EXERGY EQUATIONS OF DIFFERENT DEVICES.

Device	Operational Exergy Equation
Electrical	$P_{in} \times (1 - \eta)$
Diesel Generator	$P_{in} \times \left(\frac{\varphi}{\eta} - 1\right)$
CRAC	$Q_{in} \times \left(1 - \frac{T_{cold}}{T_{room}} + \frac{1}{\mu}\right)$
Chiller	$Q_{in} \times \left(\frac{1}{COP} - \frac{T_{tower} - T_{chilled}}{T_{chilled}}\right)$
Cooling Tower	$Q_{in} \times \left(1 - \frac{T_{amb}}{T_{warm}} + \frac{1}{\mu}\right)$

In this table, η is the delivery efficiency; P_{in} is the total input power of the electrical device; φ is the exergy correction; Q_{in} is the total thermal input of the device; T_{room} is the data center room temperature; T_{cold} corresponds to the CRAC's cold water temperature; μ is the ratio of the maximum cooling power by the maximum power consumption; COP is the coefficient of performance; T_{tower} is the water temperature that goes to the cooling tower; $T_{chilled}$ corresponds to the chilled water temperature; T_{amb} is the ambient temperature; T_{warm} corresponds to the warm water from chillers. Since the physical behavior of each device is not the focus of this work, the reader should refer to [11][12]. The algorithm that quantifies the operational exergy consumption is not presented due to the lack of space.

B. Dependability Models

Reliability Block Diagram (RBD) is a combinatorial model that has been adopted to calculate dependability metrics on large and complex systems. For examples and closed-form equations, the reader should refer to [3].

SPN Models

This work adopts a particular Petri net extension, namely, Stochastic Petri Nets (SPN) [2], which allows the association of probabilistic delays to transitions using the exponential distribution. This section presents only one proposed SPN model.

Cold standby. A cold standby redundant system is composed by a non-active spare module that waits to be activated when the main active module fails. Figure 2 depicts the SPN model of this system, which includes four places, namely X_ON, X_OFF, X_Spare1_ON, X_Spare1_OFF that represent the operational and failure states of both the main and spare modules, respectively. The spare module (Spare1) is initially deactivated, hence no tokens are initially stored in places X_Spare1_ON and X_Spare1 $\_OFF$. When the main module fails, the transition $X\_Activate\_Spare1$ is fired to activate the spare module.

Table II presents the attributes of each transition of the model. Once considering reliability evaluation (number of tokens (#) in the place $X\_Rel\_Flag = 1$), the X_Repair, $X\_Activate\_Spare1$ and X_Repair_Spare1 transitions receive a huge number (many times larger than the associated MTTF or MTActivate) to represent the absence of repair. The MTActivate corresponds to the mean time to activate the spare module. Besides, when considering reliability, the weight of the edge that connects the place X_Wait_Spare1 and the $X\_Activate\_Spare1$ transition is two; otherwise, it is one. Both availability and reliability may be computed by the probability $P\{\#X\_\ ON = 1$ OR $\#X\_Spare1\ \_ON = 1\}$.

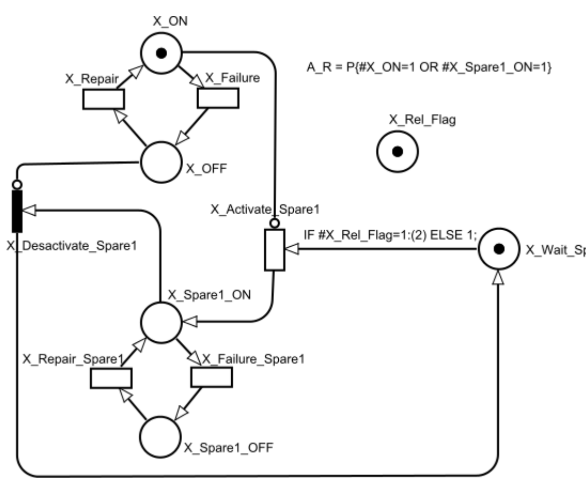

Figure 2. Cold standby model.

V. Case Study

The focus of this case study is to perform dependability analysis of real-world data center cooling architectures (from HP Labs Palo Alto, U.S. [13]) as well as to propose new infrastructures for that system. The environment ASTRO was adopted to conduct the evaluation of five cooling infrastructures. ASTRO was validated through our previous works [14] [15]. In addition to compute dependability metrics, ASTRO is adopted for estimating cost and sustainability impact as well as to to conduct the energy flow evaluation.

Table II
Cold standby model - Transition attributes.

Transition	Priority	Delay or Weight
X_Failure	-	X_MTTF
X_Repair	-	IF #X_Rel_Flag=1:(10^{13} x X_MTTF) ELSE X_MTTR
X_Activate_Spare1	-	IF #X_Rel_Flag=1:(10^{13} x MTActivate) ELSE MTActivate
X_Failure_Spare1	-	X_MTTF_Spare1
X_Repair_Spare1	-	IF #X_Rel_Flag=1:(10^{13} x X_MTTF_Spare1) ELSE X_MTTR_Spare1
X_Desactivate_Spare1	1	1

Cooling Architectures

From the baseline infrastructure (C1) depicted in Figure 3, we propose other architectures. The cooling system is responsible, in this work, for extracting 500kJ of heat from the data center room. The cooling infrastructure C1 fails (and, thus, the system) whenever one CRAC or any other component (e.g., chiller and cooling tower) that may contribute for the bad functioning of the air conditioning system fails.

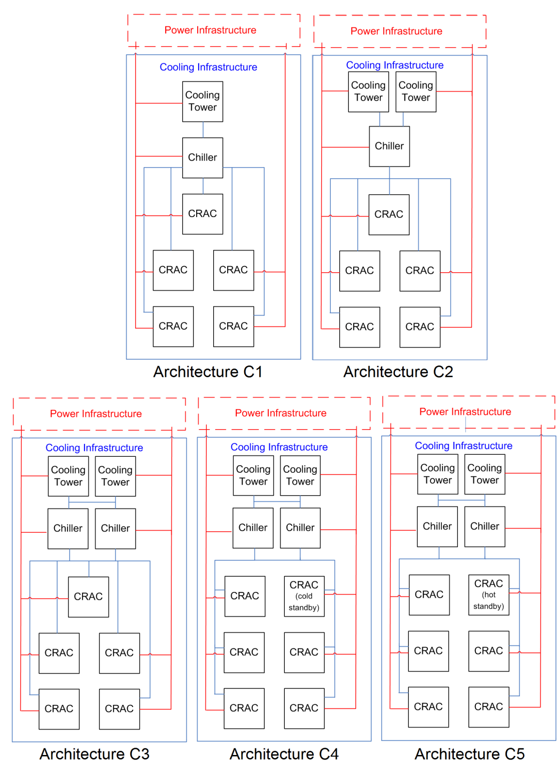

Figure 3. Cooling infrastructures.

Starting from the baseline architecture C1, four new architectures are generated according to the proposed RCI index shown in Table III. For instance, architecture C2 is proposed adopting the redundancy on the Cooling Tower (highest RCI value in the architecture C1). Similarly, architecture C3 corresponds to the architecture C2 with redundant Chiller.

Table III
RELIABILITY IMPORTANCE VALUES OF ARCHITECTURES C1-C3.

	RI			RCI		
Architecture	Chiller	Cooling Tower	CRAC	Chiller	Cooling Tower	CRAC
C1	0.22	0.19	0.17	0.17	0.18	0.14
C2	0.10	0.08	0.30	0.23	0.05	0.19
C3	0.08	0.26	0.23	0.09	0.07	0.27

In the Architectures C4 and C5, an additional CRAC unit is considered as a cold and hot standby component, respectively. A chiller, a cooling tower and 5 CRAC units are demanded for the cooling data center environment be working. For each architecture, availability, sustainability impact and costs are estimated over a period of 1 year.

Models

Figure 4 depicts the Energy Flow model for the cooling architecture C4. The evaluation of this model provides the sustainability impact and cost issues as well as the verification of the energy flow in each component (Section IV-A). In architecture C4, the sixth CRAC is only activated once one of the other CRACs has failed. Figure 5 shows the correspondent SPN model to that system. The availability is computed by the following probability $P\{\wedge_{i=1}^{5}$((#CRACi_ON=1)∨(#CRAC6_ON=1))∧($\vee_{j=1}^{2}$((# Chiller j_ON= 1)∧((#C_Tower_1_ON=1)∨(#C_Tower_2_ ON=1))))$\}$. The MTTF and MTTR values were obtained from [16].

In order to mitigate the complexity of that model, an hierarchical approach is adopted. The highlighted subnets on that figure can be evaluated separately through a RBD model. Besides, once obtained the results of both models, a RBD model with two blocks (considering the results of those RBD and SPN models) in a serial arrangement is created. The evaluation of that RBD provides the dependability results of the system.

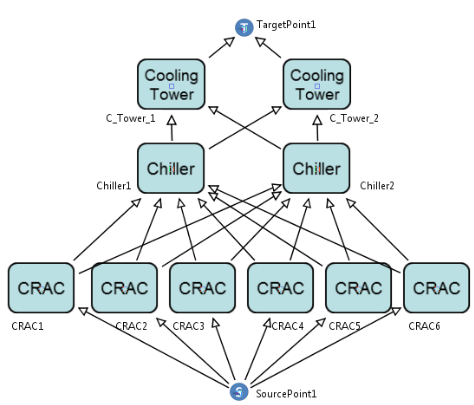

Figure 4. Energy Flow Model for the cooling architecture C4.

Results

Table IV summarizes the results separately for each cooling infrastructure, in which: *Architec* represents the architecture evaluated; *Avail(%) (9's)* is the availability level (A) with the respective number of nines (-*log*[1 - A/100]); *Down(h)* is the system downtime considering the period of 8760 hours (i.e., 1 year); *EX(GJ)* is the operational exergy consumption in gigajoule; *ACQ(USD)* and *OPER(USD)* correspond to the acquisition and operational costs in U.S. dollars, respectively.

The availability increases and the downtime decreases when redundant components are included. For instance, the availability of architecture C2 is around 10% higher than the one in architecture C1. C4 and C5 are the architectures with more redundant devices. Considering the availability results of those architecture C4 and C5, a small difference is obtained (4.96 and 4.94, respectively in nines (9's)). Similar exergy consumption and as cost are also obtained for that two architectures.

Table IV
SUMMARY RESULTS OF COOLING INFRASTRUCTURES.

Architec	Avail(%) (9's)	Down(h)	EX(GJ)	ACQ(USD)	OPER(USD)
C1	99.43413 (2.25)	49.56	9096.52	199000.00	285733.21
C2	99.69859 (2.52)	26.40	9120.72	208000.00	286493.16
C3	99.89106 (2.96)	9.54	9138.32	248000.00	287046.24
C4	99.99890 (4.96)	0.09	9148.19	278000.00	287356.12
C5	99.99885 (4.94)	0.10	9148.18	278000.00	287355.98

Figure 6 depicts a graphical comparison between the availability, cost and the operational exergy consumption for each cooling infrastructure architecture in comparison to the baseline architecture C1. As the reader should note, architectures C4 and C5 provide the highest availability (around 120% higher than C1). Besides, also considering those architectures C4 and C5, the operational exergy consumption is similar to architectures C1 to C3.

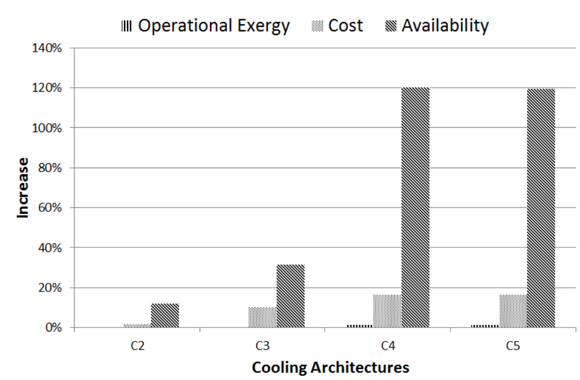

Figure 6. Cooling results: comparing Exergy, Availability and Cost.

VI. CONCLUSION

Data center availability has accomplished greater concerns due to increased dependence on Internet services (e.g., Cloud

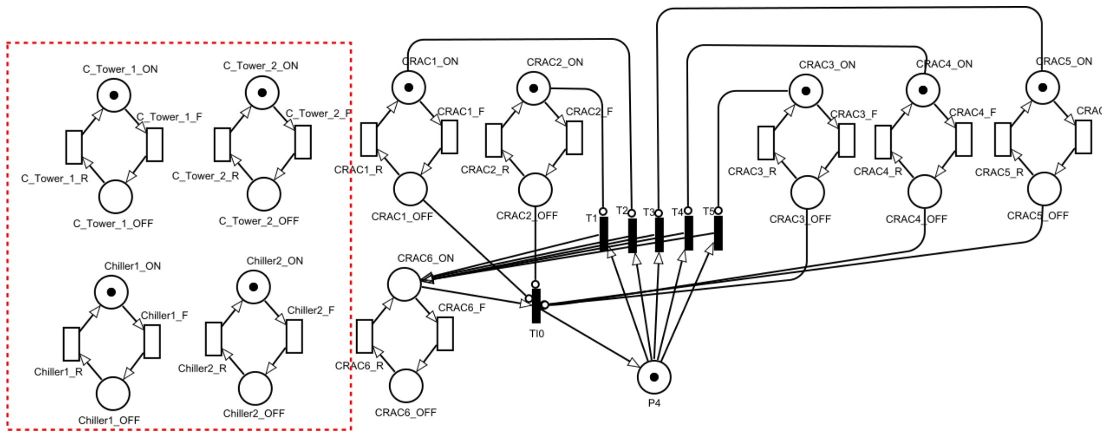

Figure 5. SPN model for the cooling architecture C4.

computing paradigm). For companies that heavily depend on the Internet for their operations, service outages can be very expensive, easily running into millions of dollars per hour. A widely used design principle in fault-tolerance is to introduce redundancy to enhance availability. However, since redundancy leads to additional use of resources and energy, it is expected to have a negative impact on sustainability and the associated cost.

At present stage, data center designers do not have many mechanisms to support the integrated sustainability, cost and dependability evaluation of data center infrastructures. This work try to reduce that gap by proposing models (supported by the developed environment ASTRO) that can be adopted before implementing data center architectures. The adopted methodology considers the advantages of both stochastic Petri Nets (SPN) and Reliability Block Diagrams (RBD) formalisms to analyze data center infrastructures.

VII. Acknowledgments

The authors would like to thank CNPQ for financing the project (290018/2011-0) and supporting the development of this work as well as the reviewers comments.

References

[1] "Microsoft - creating a greener data center," http://www.microsoft.com/presspass/features/ 2009/apr09/04-02Greendatacenters.mspx, 2009.

[2] K. Trivedi, *Probability and Statistics with Reliability, Queueing, and Computer Science Applications*, 2nd ed. Wiley Interscience Publication, 2002.

[3] W. Kuo and M. J. Zuo, *Optimal Reliability Modeling - Principles and Applications*. Wiley, 2003.

[4] B. Wei, C. Lin, and X. Kong, "Dependability modeling and analysis for the virtual data center of cloud computing," in *IEEE - HPCC*, sept. 2011, pp. 784 –789.

[5] D. Gmach, Y. Chen, A. Shah, J. Rolia, and C. Bash, "Profiling sustainability of data centers," in *Sustainable Systems and Technology (ISSST), 2010 IEEE International Symposium on*. IEEE, 2010, pp. 1–6.

[6] J. Chang, J. Meza, P. Ranganathan, C. Bash, and A. Shah, "Green server design: beyond operational energy to sustainability," in *HotPower*, 2010.

[7] M. Arregoces and M. Portolani, *Data center fundamentals*, ser. Fundamentals Series. Cisco, 2003.

[8] C. Belady, "In the data center, power and cooling costs more than the it equipment it supports," *Electronics Cooling Magazine*, February 2007.

[9] C. Ebeling, *An Introduction to Reliability and Maintainability Engineering*. Waveland Press, 1997.

[10] I. Dincer and M. A. Rosen, *EXERGY: Energy, Environment and Sustainable Development*. Elsevier Science, 2007.

[11] M. J. Moran and H. N. Shapiro, *Fundamentals of Engineering Thermodynamics*, 5th ed. John Wiley Sons, Inc., 2006.

[12] Y. A. Cengel and M. A. Boles, *Thermodynamics an Engineering Approach*, 5th ed., 2003.

[13] M. Marwah, P. Maciel, G. Callou, and B. Silva, "Quantifying the sustainability impact of data center availability," *SIGMETRICS Perform. Eval. Rev.*, vol. 37, pp. 64–68, March 2010.

[14] G. Callou, P. Maciel, F. Magnani, and J. Figueiredo, "Estimating sustainability impact, total cost of ownership and dependability metrics on data center infrastructures," in *Sustainable Systems and Technology (ISSST), 2011 IEEE International Symposium on*, may 2011, pp. 1 –6.

[15] G. Callou, P. Maciel, E. Tavares, and F. Magnani, "Sustainability and dependability evaluation on data center architectures," in *Systems, Man, and Cybernetics (SMC), 2011 IEEE International Conference on*, oct. 2011, pp. 398 –403.

[16] *IEEE Gold Book 473, Design of Reliable Industrial and Commercial Power Systems.*