Dependability and Sensitivity Analysis in Dense Data Centers Networks

***Abstract*—The design, implementation, and maintenance of data center networks must meet numerous dependability requirements to guarantee the quality of service at a high level of reliability. This paper investigates dependability metrics and performs sensitivity analysis for data center networks with different redundancy levels. Our approach is based on hierarchical modeling in which we use reliability block diagrams. We applied the parametric sensitivity analysis technique in the proposed experiments to assess how sensitive the availability is concerning the failure and repair times of the model components.**

***Keywords*—dependability; reliability; availability; sensitivity analysis; data centers networks.**

I. Introduction

One of the main challenges in a data center (DC) project is to achieve high availability according to the redundancy level for each tier. The two main factors governing downtime are equipment design and maintenance philosophy. Achieving good repair times involves simplifying diagnosis and repair. Thus, designers must understand where the main bottlenecks are and the system's failure modes to work on the maintenance strategies [1].

Low-reliability equipment must be more accessible and more easily removable to avoid further disturbance in maintenance or failure times. Given this concern, this paper proposes a set of models for data center networks in order to investigate the behavior of reliability in the face of different evaluation periods. We present the availability and the MTTF resulting from each model and apply the parametric sensitivity technique to observe the components' effect on the system's availability.

Some works has been directed with a focus on improvements for networks and data center projects. In [2], the authors present a fault tree and Markov chain models to identify the dependency between the components of a Blade Center System, presenting the failure states and the systems' availability. This work is the source of the MTTF of our research components to represent the Blade Center. In [3], the authors use Markov chains to perform a sensitivity analysis on a computer network with redundancy mechanisms to find the system availability bottlenecks. In [4], the authors take a hierarchical modeling approach with a generalized colored stochastic Petri net (CGSPN) for the IT infrastructure to assess and analyze the reliability of the active-active cloud data center service. In [5], the authors try to resolve a gap in monitoring energy consumption in the consolidation of virtual machines in a data center by proposing a tool capable of monitoring performance and estimating energy consumption. These works diverge by our modeling techniques, purpose, and contribution.

The rest of this paper is organized as follows. Section II shows the fundamentals of what was covered technically in this study. Section III describes the modeling approach for the models' construction, experiments, and results of the different data center networks. Section IV presents the final considerations, limitations, and proposals for future work.

II. Fundamental Concepts

A. Dependability for Data Centers Networks

A data center's infrastructure should generally offer a minimum availability of 99.67% for tier 1, 99.749% for tier 2, 99.982% for tier 3, and 99.995% for tier 4. However, to support highly reliable systems, the ideal would be that this number should be at least 99.9%, considering the capacity of withstanding failures. Each additional "nine" increases the order of magnitude of availability by a factor of 10. Thus, an increase from 99.99% to 99.999% is quite essential and represents a tenfold cost in investment [6].

The "everything-as-a-service" delivery offered by DC infrastructures has strict requirements for performance tolerance and service dependability. The dependability of a system allows the delivery of a service in a reliable way [7]. The dependability attributes make it possible to obtain quantitative measures, which are often crucial for analyzing the services offered. Following, we highlight the metrics and techniques used in this study.

1) Reliability Analysis: It is essential to establish what constitutes a failure because only then can it be determined which failure modes, at the component level, actually render the system inoperable. The reliability block diagram (RBD) modeling technique allows the representation of systems as a set of functional blocks in series, parallel, bridge, or K-out-of-N interconnected according to each blocks' failure effect in the overall system reliability [1]. Input parameters include MTTF and MTTR.

- MTTF – Mean time to failure corresponds to the mean exposure time between consecutive repairs of a component and the next failure of that component [8]. The MTTF of a system can be calculated by Equation 1.

$$MTTF = \int_0^\infty R(t)dt \tag{1}$$

- MTTR – Mean time to repair corresponds to the mean time to replace or repair a failed component [8]. MTTRs are closely related to the maintenance policy adopted and can be achieved by Equation 2.

$$MTTR = MTTF \times \frac{UA}{A} \quad (2)$$

Where UA represents system downtime (Equation 3), and A represents system availability (Equation 4).

$$UA = 1 - A \quad (3)$$

2) Availability: It is defined as the system's ability to carry out its programmed function at a given time [8], and can be obtained by analysis or simulation of the steady-state from the Equation 4.

$$A = \frac{MTTF}{MTTF + MTTR} \quad (4)$$

B. Sensitivity Analysis

Sensitivity analysis is a technique used to determine the factors that are most relevant to the measurements or outputs of a model. In the analysis of dependability of computer systems, it is possible to apply sensitivity analysis to assist in the identification of the components that most influence the availability, reliability or performance of a system [9].

It can be used in analytical models, from the calculation of partial derivatives of metrics of interest, to provide a unique sensitivity coefficient to determine the most influential factors in the results of the model [9], [10]. This approach can find performance or availability bottlenecks in the system, thus driving improvement and optimization [11].

III. Proposed Models and Experiments

This section presents the model incomes, descriptions, and models of the components and networks, the evaluations' results, and the experiments carried out to analyze the components' sensitivity. We used Mercury Tool, version 4.8, to support modeling and analysis [12].

A. Incomes

To represent the data center networks, firstly, we model a Blade Center System. Initially, we present a model to the blade server components, and then we model a chassis, which is composed of fourteen blade servers. This system was chosen to represent the networks' access layer as they offer the greater density and efficiency [2], which are highly desired requirements for current and future networks.

Table I presents the input parameters of the first RBD model. For each component, are presented the MTTF value source, the block acronym used in the model, the name of the component, the MTTF (in hours), and the variation MTTF to be used sensitivity analysis (-50% to +50%). Note that the components that have a * have experienced a 0.8 reduction in the MTTF value. This reduction can be applied to a confidence level of 95% [1] due to the original value being provided by the manufacturer (even some components obtained from the [2] suffered this reduction because they had an unusually high MTTF and the cited paper was made in partnership with a manufacturer).

TABLE I
INCOMES FOR THE FIRST RBD MODEL - BLADE SERVER.

Source	Ab.	Component Name	MTTF (h)	MTTF (h) -50%	MTTF (h) +50%
[2]	BB	Base Blade	220,000	110,000	330,000
	CP	CPU*	50,000	25,000	75,000
	DM	Memory Bank (DIMMs)	480,000	240,000	720,000
	HD	Hard Disk Drive	200,000	100,000	300,000
	FC	Fiber Daughter Card*	260,000	130,000	390,000
	EC	Ethernet Daughter Card*	1,240,000	620,000	1,860,000

Table II presents the components of second RBD model. For this model, we created seven blocks in series, five of which are of the *K-out-of-N* type. The same description given for the data in Table I is valid for this one. For the Blade Server component, shown in the last line (Table II), the MTTF source is the first RBD model. All components of the Tables I and II received a four-hour MTTR.

TABLE II
INCOMES FOR THE SECOND RBD MODEL - CHASSIS.

Source	Ab.	Component Name (K-out-of-N)	MTTF (h)	MTTF (h) -50%	MTTF (h) +50%
[2]	MP	Midplane	310,000	155,000	465,000
	SW	Software	17,520	8,760	26,280
	OS	Power Supply (2/4)	670,000	335,000	1,005,000
	FS	Fiber Channel Switch (1/2)	320,000	160,000	480,000
	ES	Ethernet Switch (1/2)	120,000	60,000	180,000
	BW	Blower* (1/2)	620,000	310,000	930,000
1st RBD	BS	Blade Server (6/14)	27,562	13,781	41,343

Table III shows the component parameters for the others models. For the third model, which aims to represent the mean time to failure of a rack composed of five chassis, we use the MTTF calculated from the second model (second line). To represent the four data center networks' models, we use the MTTF calculated from the evaluation of the third model (Chassis Racks - sixth row). QSFP, SFP, and UTP are the types of transceivers used to connect network components. For Blade Chassis and transceivers, the MTTR is four hours due to ease of replacement. For chassis racks, routers and switches, the MTTR is eight hours. Note the components with *, which were the ones that suffered the MTTF reduction (as explained for the Table I).

B. Component Models

The first three models were created to represent the access layer components of data center networks. Initially, we describe the Blade Center System (first two), and then we represent a rack composed of five chassis.

1) First RBD model: Represents the components of a blade server (to compose a chassis). In this model, we have the components connected in series because the failure of a component represents the failure of the system (server). Figure 1 shows the first RBD model. We perform this model to reach the MTTF of the system and compose our scenarios.

TABLE III
INCOMES FOR RBDS MODELS - 3RD TO 7TH.

Source	Ab.	Component Name	MTTR (h)	MTTF (h)	MTTF (h) -50%	MTTF (h) +50%
2nd RBD	CB	Chassis Blade	4	12,634	6,317	18,952
[13]	QSFP	Quad Small Form Factor Pluggable*		1,014,000	507,000	1,521,000
	SFP	Small Form Factor Pluggable*		980,200	490,100	1,470,300
	UTP	Unshielded Twisted Pair*		240,000	120,000	360,000
3rd RBD	CR	Chassis Racks	8	28,849	14,424	43,273
[14]	RT	Router*		96,154	48,077	144,231
[15]	SW	Switch (Layer 3)*		88,684	44,342	133,027

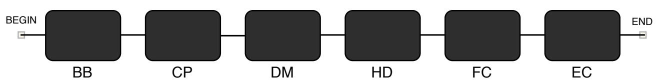


Figure 1. 1st RBD - Blade Server.

Equation 5 calculates the reliability of this system [16]. Suppose that $R_i(t)$ corresponds to the reliability of the block b_i at time t.

$$R_s(t) = \prod_{i=1}^{n} R_i(t) \tag{5}$$

2) Second RBD model: Figure 2 shows the second RBD model, whose acronyms and MTTFs of the components were presented in Table II. The general structure of the model is represented in series with some non-identical K-out-of-N (KooN) blocks. We consider that for a chassis to be considered operational, at least six of the fourteen server blades must be in operation (last block). The same reasoning is valid for the other blocks of this type.

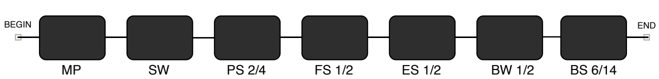


Figure 2. 2nd RBD - Chassis Blade.

Equations 5 and 6 calculates the reliability of this system [16].

$$R_s = \sum_{r=i}^{n} \binom{n}{r} R^r (1-R)^{n-r} \tag{6}$$

Where n is the total number of non-identical blocks, r is the minimum number of units required for system success. R is the reliability of each unit.

3) Third RBD model: Figure 3 presents the third RBD model, representing that each rack comprises a five-chassis. This way, we obtained the MTTF of the racks that will compose the DC networks. The structure comprises five parallel blocks (reduced figure) with the same MTTF and MTTR values.

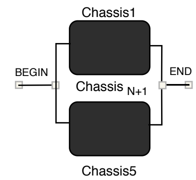


Figure 3. 3rd RBD - Chassis Rack.

Equation 7 calculates the reliability of this parallel system [16].

$$R_P = 1 - \prod_{i=1}^{n} (1 - R_i(t)) \tag{7}$$

Where $R_i(t)$ corresponds to the reliability of block b_i at time instant t.

C. Network Models

To modeling the data center networks, we consider some assumptions for good high availability network designs, an example of which is the number of particular components with a margin for growth. We assume that the networks have more robust and powerful equipment, so it is possible to reduce the amount and achieve a greater density of spaces. For example, suppose the use of 48-port routers and switches, which is sufficient to meet the current needs of networks and still support expanding the access layer without adding equipment in the core and aggregation layers. As downtime tends to be very expensive, we try to project the levels of physical redundancy for each tier, respecting each classification's specifications.

Figure 4 presents the three-layer model that is commonly used in DC networks. This type of network modularization considers both the physical and the logical design, but our focus is on the physical structure for our RBD modeling. All the tiers DC aggregate the three layers presented. In the access layer are the chassis racks that represent the network storage endpoints. The aggregation layer links the access and core layers. The core layer represents the high-speed connection point between the Internet Service Provider (ISP) and external networks for incoming and outgoing data flow. Because the chassis already have integrated switches, we abstract from the modeling the use of layer two switches.

We consider having stub networks for tiers 1, 2, and 3, with a single connection to the ISP and a single outbound path. A failure in the ISP will cause the networks to fail. Figures 5, 6, 7, and 8 show the data center networks for tiers 1, 2, 3, and 4. Due to the need for high availability, we consider that there must have a use percentage of 60%, 70%, 80%, and 90% for tiers 1, 2, 3, and 4 for all K-out-of-N blocks, respectively. For example, suppose DC tier 1, which has fifteen chassis racks, a minimum of nine (60%), must be running simultaneously for the system to be in functional mode. These percentages were determined to maximize the availability requirements according to the tier classification. To calculate the networks' reliability, an arrangement of Equations 5, 6 and 7 is made.

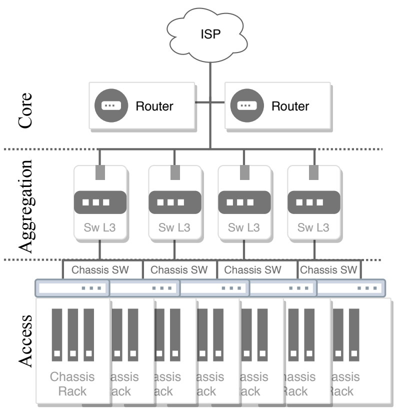


Figure 4. Three-layers Network Model.

1) Fourth RBD model: Figure 5 presents the RBD model for the tier 1 DC network. In the core layer, we have a router that connects to the aggregation layer via QSFPs transceivers. We have a layer three (L3) switch for the aggregation layer, which connects to the fifteen chassis racks via UTPs transceivers. The downstream flow happens from the core layer to the access layer, and the opposite occurs with the upstream flow (which is the same for the four networks).

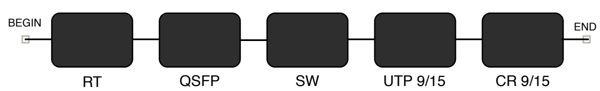


Figure 5. 4th RBD - Tier 1.

2) Fifth RBD model: Figure 6 shows the RBD model for the tier 2 DC network. The difference between this and the first model is that we have doubled the number of components, except for the router. In the central layer, we have a router that connects to the aggregation layer through QSFPs transceivers connected to two L3 switches. We have 30 chassis racks in the access layer interconnected to the aggregation layer via SFPs optical fiber links.

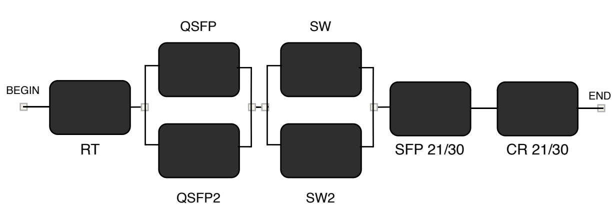


Figure 6. 5th RBD - Tier 2.

3) Sixth RBD model: Figure 7 shows the RBD model for the tier 3 DC network. We have a router connected to three aggregation switches in the central layer, which interconnect 60 racks via UTPs transceivers.

4) Seventh RBD model: Figure 8 shows the RBD for tier 4 DC network. Specifically for this tier, we added router redundancy and increase the physical links' capacity. Thus, we

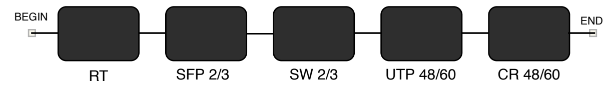


Figure 7. 6th RBD - Tier 3.

have a multi-homing stub network with two ISPs. Therefore, this network has a more remarkable ability to tolerate failures in their providers' logical/physical connection. Within these possibilities, we can have a primary link (active) with one or more links in a state of passive redundancy (e.g., hot-standby), or we can have all links active implementing some form of load balancing. However, the logical dependencies of active and passive states cannot be represented by RBDs. We have four L3 switches, which connect to routers via SFPs tranceivers and interconnect the 120 access layer racks also via SFPs.

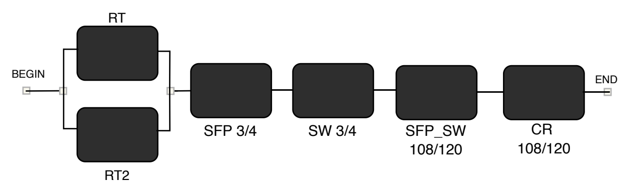


Figure 8. 7th RBD - Tier 4.

D. Outcomes

Table IV shows the evaluation results of the seven RBD models. The evaluate periods correspond to 720 and 8760 hours. The main focus for choosing these times is to show how reliability behaves. System reliability is directly related to MTTF parameters, and the system availability is directly related to MTTF and MTTR parameters [17]. Note that availability and MTTF are the same for both periods. However, for reliability, specifically for the network models (last four), the measure that we increased the components redundancy and achieved greater availability, the system's reliability decreases considerably. Likewise, the system's mean time to failure is shorter. In this sense, if we consider a tier 4 DC, which should provide a minimum availability of 99.995%, compared to a tier 1 DC, preventive maintenance must be carried out more frequently to ensure the quality of service at a high confidence level. This happens due to the need to maintain more components in simultaneous operation.

E. Parametric Sensitivity Analysis

In this paper, we applied the differential sensitivity analysis, one technique characterized by a sensitivity index known as $S_\theta(Y)$, which indicates the impact of a given measure known as Y for a parameter θ. Equation 8 shows how the percentage difference index is calculated for a metric $Y(\theta)$, where $max\left\{Y(\theta)\right\}$ and $min\left\{Y(\theta)\right\}$ are the maximum and minimum output values, respectively, computed when varying the parameter θ over the range of its n possible values of

TABLE IV
RESULTS OF EVALUATION.

Model	Evaluation Period (h)	Reliability (%)	Availability (%)	MTTF (h)
1st	720	97.42	99.98548	27,562
	8760	72.77		
2nd	720	95.74	99.97588	12,634
	8760	58.37		
3rd	720	99.99	1	28,849
	8760	96.87		
4th	720	98.38	99.98226	16,274
	8760	80.11		
5th	720	99.24	99.99168	10,675
	8760	68.57		
6th	720	99.23	99.99167	6,668
	8760	15.42		
7th	720	99.95	99.99999	3,281
	8760	8.47E-06		

interest. If $Y(\theta)$ is known to vary monotonically, only the extreme values of θ (i.e., θ_1 and θ_n) may be used to compute $max\{Y(\theta)\}$; $min\{Y(\theta)\}$, and subsequently $S_\theta(Y(\theta))$. Each $S_\theta(Y)$ is calculated by fixing the other parameters' values [18].

$$\mathrm{S}_\theta(\mathrm{Y}) = \frac{\max\{\mathrm{Y}(\theta)\} - \min\{\mathrm{Y}(\theta)\}}{\max\{\mathrm{Y}(\theta)\}} \tag{8}$$

Based on identifying the essential components, we can establish prioritization actions concerning their maintenance and replacement. In this way, it is possible to suggest the most efficient way to operate and maintain its status. Thus, we conducted a sensitivity analysis for the models created, except for the third RBD model, given that it presents only components of equal importance. We vary the MTTF and MTTR of each component between -50% to +50% of the original value to perform the sensitivity analysis. The MTTF variation is shown in the last two columns of Tables I, II, III. For components with a 4-hour MTTR, we range from 2 to 6, and with an MTTR of 8, we run from 4 to 12.

Table V shows the rank by the sensitivity index, with the five most important components for availability, the sensitivity value, and the reboot component, that is, the one that will have the least significant impact on the system's availability. In most cases, the most critical elements for availability are also more essential for reliability.

Figure 9 shows the impact of the essential components on system availability. For all models, MTTF variation had a more significant impact than the MTTR. All graphs were plotted using the same scale of availability (y-axis), which ranges from 99.95% to 100%. Note that the way the networks were represented, they all reach the availability that is suggested for each tier (as described in Section II-A).

For the first and second models, the MTTF of the CPU and software have the most significant impact on the Blade Center System (Figure 9(a) and 9(b)). Considering that the software is the component that has the lowest original MTTF presented

TABLE V
SENSITIVITY RANKING.

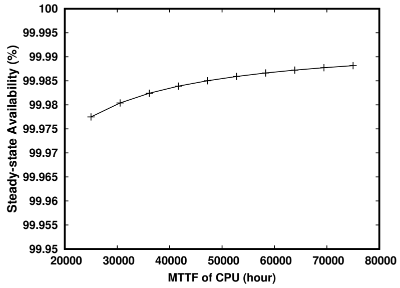
Model	Component	Rank	Value	Reboot
1st	mttf_CPU	1st	1.07E-04	mttr_EthernetCard
	mttr_CPU	2nd	8.00E-05	
	mttf_HD	3rd	2.67E-05	
	mttf_BaseBlade	4th	2.42E-05	
	mttf_FiberCard	5th	2.05E-05	
2nd	mttf_Software	1st	3.04E-04	mttr_B_Server
	mttr_Software	2nd	2.28E-04	
	mttf_Midplane	3rd	1.72E-05	
	mttr_Midplane	4th	1.29E-05	
	mttf_EtherSwitch	5th	3.95E-09	
3rd	–	–	–	–
4th	mttf_SW	1st	1.20E-04	mttr_CR
	mttf_RT	2nd	1.11E-04	
	mttr_SW	3rd	9.02E-05	
	mttr_RT	4th	8.32E-05	
	mttf_QSFP	5th	5.26E-06	
5th	mttf_RT	1st	1.06E-04	mttr_SFP
	mttr_RT	2nd	7.39E-05	
	mttf_SW2	3rd	1.08E-08	
	mttf_SW	4th	7.23E-09	
	mttr_SW	5th	7.23E-09	
6th	mttf_RT	1st	1.11E-04	mttr_UTP
	mttr_RT	2nd	8.32E-05	
	mttf_SW	3rd	8.68E-08	
	mttr_SW	4th	4.88E-08	
	mttf_CR	5th	1.96E-08	
7th	mttf_CR	1st	1.23E-05	mttr_SFP
	mttr_CR	2nd	6.90E-06	
	mttf_SW	3rd	1.73E-07	
	mttr_SW	4th	9.76E-08	
	mttf_RT2	5th	9.23E-09	

(two years), it is precisely in the second model that we find the least availability (see Table IV).

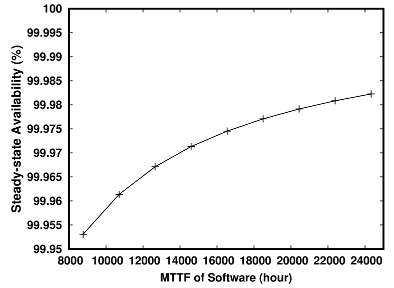
For the network graphs (Figure 9(c) to 9(f)), we can see the difference between the variation in availability, especially between tiers 1 and 4 (Figure 9(c) and 9(f)). For tier 1, even raising the MTTF of the Switch to +50% of the original value, the availability does not exceed 99.985%. This is due to the absence of component redundancy. For tier 4, which has the highest level of redundancy between components, availability is the highest.

IV. CONCLUSION

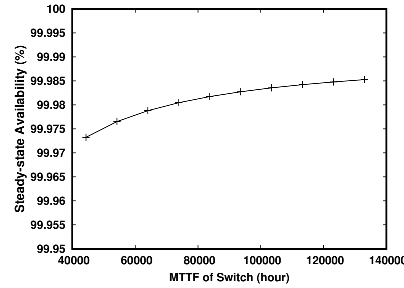
In this study, we propose RBD models to analyze some dependability metrics. The proposed models aims to represent a Blade Center system's components, which is used as storage endpoints of four data center networks that are modeled with different levels of redundancy, according to the tier classification. We present the reliability behavior when the redundancy levels increase, making a comparison between evaluations with one month (720h) and one year (8760h). The sensitivity analysis was applied to guide the optimization of the system in terms of steady-state availability. The most important components were presented as well as the one that has the least impact on availability. As limitations of our research, we can mention that the original MTTF values used do not represent the plurality provided by the different manufacturers or found in the literature. The second limitation is that we



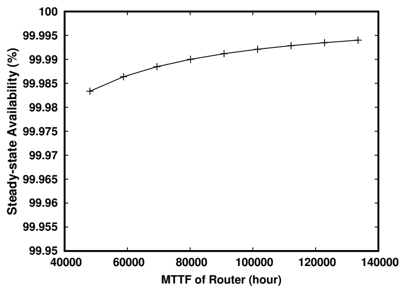
(a) 1st model



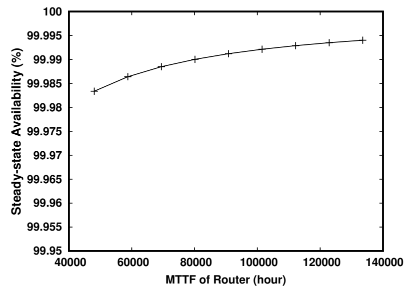
(b) 2nd model



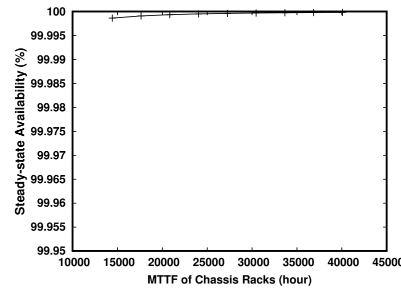
(c) 4th model



(d) 5th model



(e) 6th model



(f) 7th model

Figure 9. Effect of Each 1st Rank Component on Systems' Availability

represent the minimum necessary number of components to fit into the tier classifications. Still, in general, the actual data center infrastructure has many more features. For future work, we plan to extend models based on Markov chains to represent logical redundancy mechanisms and compute the system's probability of entering a particular failure state.

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