Modeling and Analyzing Power System Failures on Cloud Services

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***Abstract*—Many enterprises rely on cloud infrastructure to host their critical applications (such as trading, banking transaction, airline reservation system, and credit card authorization). The unavailability of these applications may lead to severe consequences that go beyond the financial losses, reaching the cloud provider reputation too. However, to maintain high availability in a cloud data center is a difficult task due to its complexity. The power subsystem is crucial for the entire operation of the data center because it supplies power for all other subsystems, including IT components and cooling equipment. Some studies have already proposed models to evaluate the availability of the power subsystem, but none of them are based on standard redundancy models. Standards guide cloud providers regarding availability, points of failure, and watts per square foot based on components' redundancy. This paper proposes RBD and Petri Net models based on the TIA-942 standard to estimate the availability of the data center power subsystem and analyze how failures on power subsystem impact the availability of critical applications. These models are important to resource planning and decision making by the cloud providers, because they may identify which components they ought to invest in order to improve the availability level.**

I. INTRODUCTION

A recent study analyzed the cost behavior of unplanned data center outages in the past 6 years, and found that the average cost has increased from \$505,502 in 2010 to \$740,357 in 2016 [1]. UPS (uninterruptible power supply) failure remains at the top of the list causing around 25% of unplanned failures; followed by DDoS attacks, human error, and cooling system failure. The UPS is one of many components that are part of the power subsystem. This subsystem is one of the largest and the most complex ones in a data center. It consists of many facilities and structures, components and equipment, with complex interactions among all those [2].

From the cloud provider viewpoint, these failures are still hard to manage and prevent. Note also that the larger a data center is the greater is its downtime cost. A common strategy is to apply component redundancy to ensure reaching higher availability at minimum costs.

Some standardization bodies work on defining a classification that allows comparing data centers according to their availability. Such classification may be based on tiers (ITU and TIA-942 standards) or Classes of availability (BICSI-002 and EN-50600 standards) and describes how redundant components can be added to increase the availability level.

In this work, we propose a set of power subsystem models based on the TIA-942 standard; for that, we use Petri Net in order to understand how their failures impact on the overall data center availability. We also provide a sensitivity analysis to detect which power components are more sensible to failures and how they bias the availability level.

In summary, our contributions can be defined as: *(a)* to propose stochastic models based on TIA-942 standard to represent the power subsystem of a cloud data center; *(b)* to evaluate those models regarding their availability (stationary simulations), reliability (transient simulations), and sensitivity (percentage difference method); and *(c)* to model a critical application and propose a model to integrate the critical application with the power subsystem.

II. DATA CENTER INFRASTRUCTURE

Data center standards define fundamental aspects, best practices, and recommendations regarding data center design and infrastructure. According to them, a generic data center system is basically composed of three subsystems: i) power infrastructure, ii) cooling infrastructure, and iii) IT infrastructure.

Those standards also define a classification that allows comparing data centers according to their availability level. Such classification may be based on tiers (ITU and TIA-942 standards) or Classes of availability (BICSI-002 and EN-50600 standards). In this work, we focus on the power subsystem and our proposal models are based on the TIA-942 tier classification.

Tier classification ranges from I to IV and higher tiers inherit requirements of lower ones. For instance, in tier I, there is no redundancy, Tier II must be less susceptible to system disruptions, tier III may avoid system disruptions, and tier IV should be fault tolerant. Higher tiers provide greater availability, which understandably result in higher costs and operational

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complexities. Therefore, the tier selection depends on the business requirements, such as minimum service availability, employment costs, and downtime financial consequences.

Basically, a tier is different from another one due to the number of redundant components and distribution paths. The redundant components refer to the number of IT equipment, cooling, and power components that comprises the data center infrastructure. In tier I, N means no redundancy indicating that system failures will result in outages. While in tiers II, III, and IV $N+1$ means that there is some level of component redundancy. The number of delivery paths refers to the number of distribution paths of the power and cooling systems serving the IT equipment [3].

A. Power Subsystem

The data center power subsystem is responsible for feeding non-essential, essential, and critical loads. The non-essential (lighting, work stations, and supplementary equipment) loads may be interrupted without impacting the data center availability. However, the essential and critical loads impact in the data center availability. The essential loads refer to mechanical and cooling units. Essential loads affect indirectly the data center availability, that means, once the power to the cooling subsystem is interrupted, the IT equipment will continue operating for a while, until it gets warm, and turns off. Lastly, we have the critical loads composed of the IT equipment. Faults in the power components that feed the critical load directly affect the overall data center availability.

A typical data center power system infrastructure includes a utility substation, an alternate power source, a transfer switchgear or an Automatic Transfer Switch (ATS), an Uninterruptible Power Supply (UPS) system, and a Power Distribution Unit (PDU).

A data center is powered by a utility substation and may also contain an alternative power feed (such as solar, wind, bioenergy, hydroelectric and wave) [4]. Both primary and secondary power sources are connected to an ATS. The ATS provides input for the non-essential, essential, and critical loads. Following the critical load distribution path, the ATS feeds the UPS system (batteries). Then, the UPS system routes power to the PDU (rack socket for cabinets). Lastly, the PDU distributes electrical energy to the IT equipment.

According to the TIA-942 standard, in a tier I data center power subsystem there is no redundancy. A single distribution path (non-redundant) feeds the IT equipment.The standard recommends $N+1$ redundant generator and UPS to the tier II. As in tier I, the tier II has a single distribution path serving the computer equipment.

III. POWER SUBSYSTEM MODELS

This section presents our models regarding power subsystem tier I (subsection III-A) and II (subsection III-B). To better understand our proposal, we present the model divided in a set of operational building blocks.

A. Tier I

Each electrical component (utility, generator, ATS, UPS, and PDU) is modeled as a building block composed of two places (indicating its state, UP or $DOWN$) and two timed transitions (indicating its repair and failure rates). The list of all guard functions used in the Petri Net are described in Table I. Table II presents complementary variables of our models, that have constant values, such as the battery discharge time and the required time to start the generator.

TABLE I
GUARD FUNCTIONS OF POWER SUBSYSTEM - TIER I AND II

Transition	Guard Function
PW_NET_1	#PW_GENERATOR_1_UP=0
PW_IT_4	((#PW_UTILITY_1_UP=0)AND(#PW_GENERATOR_1_UP=0)) OR(#PW_ATS_1_UP=0)
PW_IT_3	((#PW_UTILITY_1_UP>0)OR(#PW_GENERATOR_1_UP>0)) AND(#PW_ATS_1_UP>0)
PW_IT_18	(#PW_MAINSWB_1_UP=0)AND(#PW_UPSMODULE_1_UP>0) AND(#PW_BATTERY_1_UP=0)
PW_IT_17 PW_IT_19	#PW_MAINSWB_1_UP=1
PW_IT_6	((#PW_MAINSWB_1_UP=1)AND((#PW_UPSBYPASS_1_UP=0) AND(#PW_UPSMODULE_1_UP=0)))OR((#PW_MAINSWB_1_UP=0) AND(#PW_UPSMODULE_1_UP=0))OR((#PW_BATTERY_1_DOWN>0) AND((#PW_AVBATTERY=0)AND(#PW_BATTERY_1_UP=0)))
PW_IT_5	((#PW_MAINSWB_1_UP=1)AND((#PW_UPSBYPASS_1_UP>0) OR(#PW_UPSMODULE_1_UP>0)))OR((#PW_UPSMODULE_1_UP>0) AND(#PW_BATTERY_1_UP=1))
PW_IT_16	#PW_MAINSWB_1_UP=0
PW_IT_15	#PW_MAINSWB_1_UP=1
PW_IT_8	(#PW_SECONDSWB_1_UP=0)OR(#PW_PDU_1_UP=0)
PW_IT_7	(#PW_SECONDSWB_1_UP=1)AND(#PW_PDU_1_UP>0)

TABLE II
ADDITIONAL VARIABLES

Variable	Value (h)	Comments	Transition
PW_DELAY_GENERATOR_1 [5]	0.05278	Time to start the generator	`PW_NET_1`
PW_DISCHARGE_BAT_1 [5]	0.117	Battery runtime	`PW_NET_2`

Next, we explain in detail these building blocks, how they are interconnected and their guard functions.

1) Utility, generator and ATS components: Figure 1 shows the Petri Net regarding utility (`PW_UTILITY_1_UP/DOWN`), generator (`PW_GENERATOR_1_UP/DOWN`), and ATS (`PW_ATS_1_UP/DOWN`) components, connected through the (`PW_MAINSWB_1_UP/DOWN`) building block.

The utility is the main power supply to the Data center and when it fails, the generator, if available (`PW_AVGENERATOR_1_UP`), will feed the data center. The time needed to start the generator is represented by the non-exponential transition `PW_NET_1`. This transition has a guard function that ensures that a single generator will be turned on (helpful when we have redundant generators, as in tier II). Once the utility is repaired, the generator is turned off and it will be available for future needs (see the immediate transition `PW_IT_2` in Figure 1). Note that this transition (`PW_IT_2`) has no guard functions.

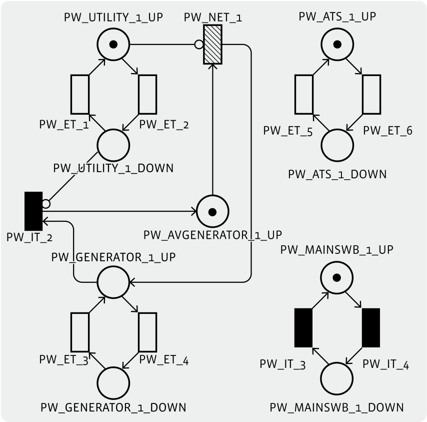

Fig. 1. Utility, generator, and ATS components

The ATS component switches between utility and generator power sources and forwards the energy to the entire data center. There is a building block composed of places (`PW_MAINSWB_1_UP/DOWN`) that represents if the utility, generator, and ATS are feeding the data center (non-essential, essential, and critical loads).

In that case, they will be able to determine if the utility or the generator is working and the ATS is operating (immediate transition `PW_IT_3`). On the other hand, they will not be able to feed the data center if both utility and generator have failed or if only itself has failed (see the immediate transition `PW_IT_4`).

2) UPS component: The UPS component Petri Net is shown in Figure 2. The UPS is composed of a static bypass and a UPS module integrated with the batteries. We point out that the UPS only feeds the data center critical loads, such as the IT equipment. Normally, the energy from the ATS passes through the UPS module, charging the batteries. Therefore, the static bypass is only used when the UPS module fails; so it acts as an alternative path inside the UPS component. In that configuration, the data center critical load will not be protected by the batteries. Hence, it will be more susceptible to disruptions.

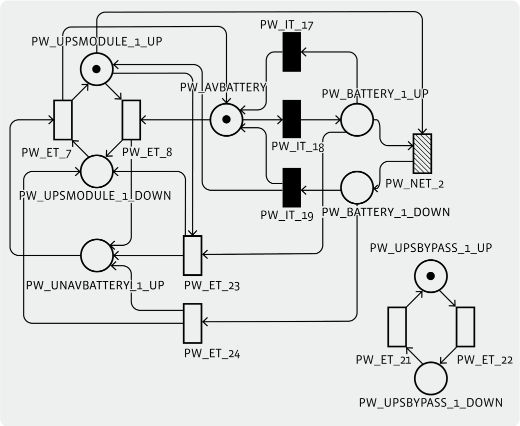

Fig. 2. The UPS components: static bypass, UPS module and batteries

As the UPS module and the batteries are strictly related to each other, we modeled them together. There is a UPS module and a battery available for use (see places `PW_UPSMODULE_1_UP/DOWN` and `PW_AVBATTERY`).

We modeled the failure of the UPS module while it is in the following three different states (1) not using the batteries (see the exponential transition `PW_ET_8`), (2) while using the batteries (see `PW_ET_23`), and (3) when the battery is discharged (see `PW_ET_24`). All of these transitions have the same value (MTTF/MTTR of UPS module) and their failure will put the UPS module in the place named `PW_UPSMODULE_1_DOWN` and its battery in place `PW_UNAVBATTERY_1_UP`.

The immediate transitions denote when the use of batteries is required or not. The batteries must be used while the generator is starting after a utility failure or if the utility, generator, and ATS are not able to feed the data center, in other words, if the state of the building block is `PW_MAINSWB_1_DOWN`.

Besides, to use the batteries, the UPS module must be working and we do not have another UPS module (batteries) feeding the IT equipment (in the case of redundant UPS components) (see the immediate transition `PW_IT_18` and its guard function). On the other hand, the use of batteries is not required anymore if the data center main power feed is working (`PW_MAINSWB_1_UP`). When the main feed reactivates, the batteries may be in use (see the immediate transition `PW_IT_17`) or may be discharged (see `PW_IT_19`).

In order to simplify our model, we do not consider the time it takes to charge the batteries. But, we consider its discharging time while in use (see the non-exponential transition `PW_NET_2`). We also modeled the UPS static bypass (`PW_UPSBYPASS_1_UP/DOWN`), considering its two states (UP or DOWN) and failure and repair rates.

3) PDU component: The PDU Petri Net is shown in Figure 3, and the building block (`PW_SECONDSWB_1_UP`) represents when all the previous components are able to feed the PDU, connecting the building blocks described previously.

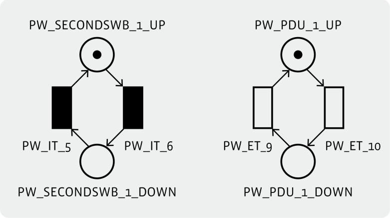

Fig. 3. The PDU component

The building block `PW_SECONDSWB_1_UP/DOWN` has two immediate transitions. The first one defines the conditions in which we have energy to the PDU (see immediate transition `PW_IT_5` and its guard function). They are: (1) if `PW_MAINSWB_1_UP` is working and the UPS component (static bypass or UPS module) is able to forward the energy, or (2) if the UPS module is working and is using the battery power. On the other hand, the latter one determines the circumstances in which we do not have energy to the PDU (see immediate transition `PW_IT_6` and its guard function). They are (1) if `PW_MAINSWB_1_UP` works and both static bypass and UPS module of the UPS component are down, or (2) if `PW_MAINSWB_1_DOWN` is not working and the UPS module (batteries) inside the UPS component is down, or lastly (3) if the battery is discharged (which signifies that the main power feed is down) and, in case of redundant UPS components, there is neither one available nor currently being used.

4) Essential and critical loads availability: Lastly, there are two building blocks regarding the power feed to the essential (mechanical and cooling) and critical loads (IT equipment), shown in Figure 4.

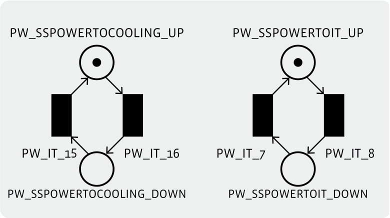

Fig. 4. Building blocks of the power feed to the essential and critical loads

These building blocks represent whether the electrical components are able or not to provide energy to the cooling and IT equipment (`PW_SSPOWERTOCOOLING_UP/DOWN` and `PW_SSPOWERTOIT_UP/DOWN`).

The building block of the essential load (utility, generator, and ATS) has two immediate transitions `PW_IT_15` and `PW_IT_16` and its state depends of the building block `PW_MAINSWB_1_UP` once the cooling feed comes from it. While, the building block of the critical load has two immediate transitions `PW_IT_7` and `PW_IT_8` and its state depends of the building block `PW_SECONDSWB_1_UP/DOWN` and the `PW_PDU_1_UP/DOWN` component, which implies that, the feed to the IT equipment depends of all electrical components in the power architecture.

The availability of the essential, A_{EL}, and critical, A_{CL}, load of the tier I is given by Eq. 1 and 2, respectively.

$$A_{EL} = P\{\#PW\_SSPOWERTOCOOLING\_UP = 1\} \tag{1}$$

$$A_{CL} = P\{\#PW\_SSPOWERTOIT\_UP = 1\} \tag{2}$$

Hence we obtain the probability of having a token in place `PW_SSPOWERTOCOOLING_UP` (for essential loads) and `PW_SSPOWERTOIT_UP` (for critical loads).

B. Tier II

According to the TIA-942 standard, a tier II data center power subsystem is composed of redundant components. The standard recommends $N + 1$ generator and UPS redundancy.

Similarly to tier I, the tier II also has a single distribution path serving the IT equipment.

It is important to highlight that the tier II Petri Net is very similar to the tier I Petri Net model, meaning that they have the same components, places, transitions, and guard functions (see Table I). However, they differ in the number of tokens in places regarding the generator (`PW_AVGENERATOR_1_UP`) and the UPS component (`PW_UPSBYPASS_1_UP`, `PW_UPSMODULE_1_UP`, and `PW_AVBATTERY`). These places have two tokens representing the tier II redundant generator and UPS components. The availability of tier II is obtained by the same equation presented for tier I, Eq. 1 and 2.

IV. EVALUATION RESULTS

We evaluated the availability and sensitivity of tier I and II power subsystem models using the Mercury tool. Furthermore, after the sensitivity analysis we conducted a reliability analysis in the components with most impact on availability. We used stationary simulations with a confidence level of 98%, maximum relative error of 5%, and simulation time of 50,000 hours. Table III presents the MTTF and MTTR values of each power component we are considering in our models.

TABLE III
MTTF AND MTTR VALUES OF POWER SUBSYSTEM COMPONENTS

Component	**MTTF (in hours)**	**MTTR (in hours)**
Utility [5]	257.26	0.032
Generator [5]	9,733.3	3.9
ATS [5]	102,093.9	5.73
UPS Bypass [6]	50,000	8
UPS Module [5]	27,472.5	8
PDU [5]	282,581	156

A. Availability Analysis

The simulation results regarding availability level are shown in Table IV. The tier I provides an availability of 99.98414% for the essential load (mechanical and cooling) and 99.93907% for the critical load (IT equipment). On the other hand, the tier II provides 99.98421% and 99.93970% of availability for the essential and critical loads, respectively.

TABLE IV
AVAILABILITY ANALYSIS REGARDING THE TIER I AND II POWER SUBSYSTEM

Tier	**Load classification**	**Availability Level (%) Confidence Interval (98%)**	**Number of nines (9's)**	**Downtime (Hour/Year)**
Tier I	Essential load	99.98414 [99.98414 - 99.98415]	3.79	1.38
	Critical load	99.93907 [99.93904 - 99.93910]	3.21	5.33
Tier II	Essential load	99.98421 [99.98421 - 99.98421]	3.80	1.38
	Critical load	99.93970 [99.93969 - 99.93972]	3.22	5.28

B. Sensitivity Analysis

The sensitivity analysis allow data center operators to find the power components with most impact on availability, as well as the impact of design changes from tier I to tier II. We used the percentage difference method implemented in the Mercury tool.

1) *Sensitivity Analysis - tier I:*

Table V shows the sensitivity ranking of the top four power components with most impact on availability in tier I. Those components are the PDU failure (`PW_MTTF_PDU_1`), PDU repair (`PW_MTTR_PDU_1`), ATS failure (`PW_MTTF_ATS_1`), and lastly ATS repair (`PW_MTTR_ATS_1`).

TABLE V
SENSITIVITY RANKING OF TIER I. TOP FOUR.

Parameter	Sensitivity Index
PW_MTTF_PDU_1	0.0001119
PW_MTTR_PDU_1	0.0001052
PW_MTTF_ATS_1	0.0000180
PW_MTTR_ATS_1	0.0000099

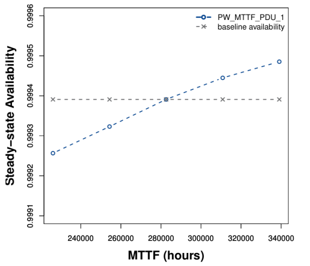

Fig. 5. Tier I: Sensitivity analysis of PW_MTTF_PDU_1.

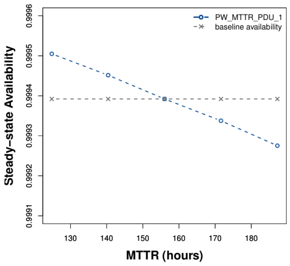

Fig. 6. Tier I: Sensitivity analysis of PW_MTTR_PDU_1.

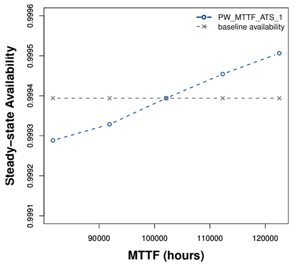

Fig. 7. Tier I: Sensitivity analysis of PW_MTTF_ATS_1.

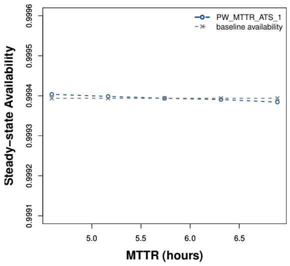

Fig. 8. Tier I: Sensitivity analysis of PW_MTTR_ATS_1.

As presented in Figure 5, from the baseline availability (point of interaction), an increase of 10% in the MTTF of the PDU increased the availability by 0.47 hours. While, an increase of 20% increased the availability by 0.83 hours. Figure 6 represents the MTTR of the PDU. From the baseline availability, an increase of 15.6 hours in the PDU repair time resulted in an availability decrease by 0.48 hours. Figures 7 and 8 represent the availability variation of the ATS component. The ATS failure has a higher impact on availability than its repair.

2) *Sensitivity Analysis - tier II:*

Table VI shows the sensitivity ranking regarding the four power components with higher impact on availability in tier II. The failure of the PDU component has the greatest impact on availability in tier II. Following we have the PDU repair, ATS repair, and the delay to start the generator.

TABLE VI
SENSITIVITY RANKING OF TIER II. TOP FOUR.

Parameter	Sensitivity Index
PW_MTTF_PDU_1	0.000116
PW_MTTR_PDU_1	0.000109
PW_MTTR_ATS_1	0.000014
PW_DELAY_GENERATOR_1	0.000013

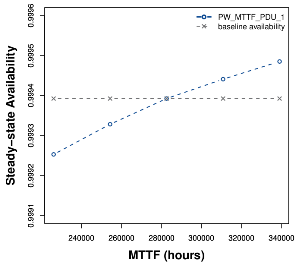

Fig. 9. Tier II: Sensitivity analysis of PW_MTTF_PDU_1.

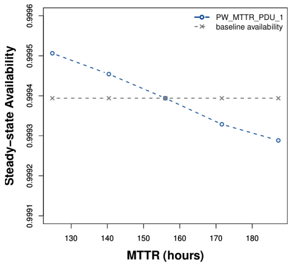

Fig. 10. Tier II: Sensitivity analysis of PW_MTTR_PDU_1.

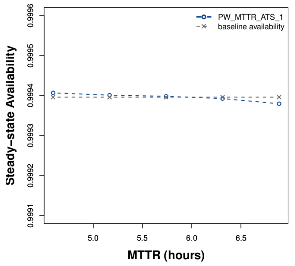

Fig. 11. Tier II: Sensitivity analysis of PW_MTTR_ATS_1.

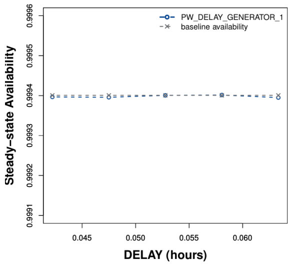

Fig. 12. Tier II: Sensitivity analysis of PW_DELAY_GENERATOR_1.

Figure 9 shows that an increase of 20% in the failure time of the PDU results in an availability increase by 0.81 hours. While, a decrease of 20% in its time to fail results in an availability decrease of 1.22 hours. In Figure 10 the impact of the repair time of the PDU in the overall availability increased by 0.98 hours (decreasing 20% from baseline) and decreased by 0.92 hours (increasing 20% from baseline).

Regarding the ATS component, Figure 11 shows that decreasing the repair time in 20%, we have an availability increase by 0.12 hours (from baseline). In Figure 12, the impact on availability regarding the time to start the generator varied from 99.9396% (when requiring 2.53 minutes) to 99.9395% (when requiring 3.8 minutes).

V. CRITICAL APPLICATION AVAILABILITY

We modeled a generic critical application using RBD. Next, we obtain its MTTF and MTTR reliability metrics in order to integrate the application to the Petri Net model that represents the power subsystem. With this, we can estimate the overall availability. We highlight that the availability evaluation considers the critical load (IT equipment) feeding.

Figure 13 shows the RBD model that represents the critical application. This system is composed of four serial components: hardware (HW), operating system (OS), virtual machine (VM) and the critical application (APP). The MTTF and MTTR values are described in Table VII.

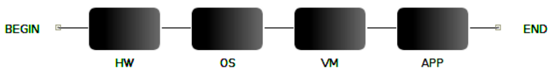

Fig. 13. RBD model of the service components based from [7]

TABLE VII
RBD PARAMETERS OBTAINED FROM [7], [8]

Components	MTTF (hours)	MTTR (hours)
HW	8760	1.667
OS	1440	1
VM	1880	0.167
APP	240	0.056

We used the Mercury tool to obtain the reliability results of the RBD model (see Table VIII). These values will be used in the integrated model described next.

TABLE VIII
RELIABILITY ANALYSIS OF THE CRITICAL APPLICATION

Metric	Result	Metric	Result
MTTF	181.58	Number of Nines	2.91
MTTR	0.21	Uptime (hours)	8755.24
Availability	0.99879	Downtime (hours)	10.57

Figure 14 shows the Petri Net model that integrates our power subsystem to the critical application. On the left side, we have the building block that represents the power feed to the IT subsystem. The guard functions (`PW_IT_7` and `PW_IT_8`) are the same for tiers I and II and were described in Table I. On the right side, the application building block is composed of two places `CRITICAL_APP_UP` and `CRITICAL_APP_DOWN`, representing the application status. It also has two exponential transitions `IT_ET_11` and `IT_ET_12`, which MTTR and MTTF values were obtained from the RBD (see Table VIII).

The availability of the integrated model is given by the probability of both, power subsystem and critical application, being working properly. See Eq. 3.

$$\begin{aligned} A_{app} = & P\{\{\#PW\_SSPOWERTOIT\_UP = 1\} \\ & AND\{\#CRITICAL\_APP\_UP = 1\}\} \end{aligned} \tag{3}$$

Table IX presents the availability results of the simulation. Tier I provides an availability of 99.8186%, and the tier II 99.8190%, being the tier II 1.8 minutes more available than tier I. Considering critical applications, such as PayPal, this difference of 1.8 minutes may represent a meaningful lost of $ 6,750 (considering that PayPal has a downtime cost of 225,000 USD/hour [9]).

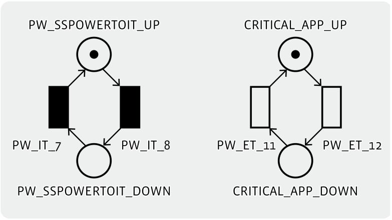

Fig. 14. Integration of the power subsystem and the critical application

TABLE IX
AVAILABILITY OF THE CRITICAL APPLICATION INTEGRATED TO THE POWER SUBSYSTEM

Tier	Load classification	Availability Level (%) Confidence Interval (98%)	Number of nines (9's)	Downtime (Hour/Year)
Tier I	Critical load	99.81861 [99.81860 - 99.81862]	2.741	15.88
Tier II	Critical load	99.81900 [99.81897 - 99.81903]	2.742	15.85

VI. CONCLUSIONS AND FUTURE WORKS

This paper presented a set of data center power subsystem models based on TIA-942 standard. We modeled a critical application and integrated it with the power subsystem model to analyze the impact of power failures in the application availability. This work is useful in answering data center planning decisions such as by investing into a subsystem how component redundancy reduces downtime. Furthermore, the results allow data center operators to make better design decisions considering critical components in order to increase the overall data center availability.

The availability results of our integrated model (power subsystem and critical application) showed that using redundant generator and UPS (tier II) reduced the application annual downtime by 0.03 hours compared to tier I (no redundancy). The sensitivity analysis results showed that the PDU and ATS are the two components that most impact on availability.

As future work, we plan to propose models regarding tier III and IV of power subsystem. We also plan to integrate the three basic subsystem of a data center (power, cooling and IT) and evaluate how failures of those subsystems affect the overall data center availability.

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