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**RESEARCH ARTICLE**

# Characterization and Development of a Model for the Determination of the Power and Cooling Reliability of a Mobile Switching Centre

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**ABSTRACT**

*The aim of this work is to characterize and develop a model for the determination of the cooling reliability of a mobile switching centre. From the analysis done with the reliability block diagram models (RBD), it was observed that the combined cooling reliability, MTBF and failure rate (λ) is 58.54%, 1389hrs and 0.000719704 respectively. Further checks on the combined cooling reliability gave 83.53% at 250hrs for the same failure rate which calls for urgent and stringent maintenance programs developed for the 250hrs cycle in addition to the already existing 744hrs cycle. This should be proactively applied to the cooling units on a need basis to increase the MTBF and the reliability of the older units to 99.982% required for high performance and public safety as specified by ANSI/TIA, especially during the heat season of the year.*

***Keywords:*** *Determination of the Power; Mobile Switching Centre; Cooling Reliability*

## Introduction

Mobile switching centres, data centres and other telecommunication facilities are classified by the government as critical national infrastructure (CNI) because their services support the economic, political, and social life of the citizens of the country. Because of its significance, any loss, whether total or partial, or compromise, might result in significant human casualties, have a negative effect on the economy, have other negative social repercussions for the community, or give the national government immediate concern. These assistance services have led to an ongoing search for immediate access to information and communications technology and the drive for subscribers to have very fast and uninterrupted service from mobile switching centres or data centres. The reliability of the data centre is extremely important to achieve guaranteed end-user satisfaction which depends on the availability of the data centre services. To achieve this, careful assessment/evaluation of the data centre medium and low voltage distribution network is done to examine and understand the system behaviour - MTTF, MTTR, MTBF, system reliability and failure rate during normal operation and a system fault in order to establish the fault(s) in the system, the parameters that are responsible for the fault and why they are not performing well. This assessment considers the reliability of the raw power which comprises the utility supply, the AVR, the automatic transfer switch, the standby power (diesel generators), the conditioned power (the UPS power supply) and the distribution topology. It also considers the installed Heating and Ventilating Air Conditioners (HVACs) installed in each of the prefab rooms to achieve optimum and sustainable cooling. The major problem has remained grid power fluctuation and instability which cause reduced Cooling Capacity due to frequent restarts and reduced MTBF of the cooling HVACs, and premature IT equipment failure due to inefficient heat removal from the prefab rooms. These cause increased operational costs because of the prolonged use of standby power supply during grid power fluctuations – equipment damage, tear and wear on DG and associated diesel cost.

The data centre reliability is evaluated using the results from the study which is developed into a model to ensure that the topology adopted is most suitable to achieve the needed redundancy and maintenance programs that will give the level of reliability needed to ensure improved power and cooling availability in the mobile switching centre/data centre. According to Yasar et al., in the data centre industry, equipment redundancy is widely utilized to achieve high system availability, often required to be in the range of 99.999% (five nines) while designs can now be certified as simultaneously "concurrently maintainable" and "fault-tolerant." In addition to eliminating single points of failure, these designs also maintain fault tolerance when equipment and systems are isolated for maintenance or repairs (Yasar et al., 2022). Because of the effects of temperature and humidity on IT equipment reliability and the corresponding impact on the business supply chain - reputational damage and impact on customer experience as the prefab room temperature rise above 30$^{o}$C, ASHRAE 2008 environmental guidelines stipulate that data centres should be maintained between 20$^{o}$C to 22$^{o}$C (McMorrow, 2019).

## Literature Review

According to the research by Afsharnia (2017) failure prediction is one of the key challenges that have to be mastered in order to achieve techniques that help with the proactive handling of faults and defined prediction as a statement about what will happen or might happen in the future. The author went further to define failure as “an event that occurs when the delivered service deviates from the correct service” (Afsharnia, 2017). The main point in his work is that failure refers to misbehaviour that can be observed by the user, which can either be a human or another computer system (Afsharnia, 2017). According to the author, things may go wrong inside the system, but as long as it does not result in incorrect output (including the case that there is no output at all) there is no failure (Afsharnia, 2017). It is also important to avoid confusion between terms of reliability and availability because while they seem similar, they have subtly different meanings. Reliability is the probability that a system performs correctly during a specific time duration (Raza, 2019). In contrast, availability “is a measure of the probability that a system/component is operational at a given time” (Frangopoulos, 2004). From a mathematical perspective, the key elements used within the design of this model are based on the work by Afsharnia, (2017), on failure rate analysis which provided the mathematical foundation for the formulas used. The use of availability formulas and the assumptions made in the model is straightforward, providing easy adaption in later iterations of the models.

Reliability engineering with regard to distribution systems involves gathering outage data and evaluating system designs (Onime & Adegboyega, 2014). The outage data comprise information on each failure event within a particular period. The information recorded in a narrative form is usually translated into a statistical database for analysis and evaluation. The outages are usually classified as forced or scheduled and provide information on failure rates and repair times of component used in the distribution system for reliability calculations and evaluation.

Below mathematical equations show the relationship used in calculating the outage hours (OH), service hours (SH), Number of Faults (NF), unplanned Outage Hours (UOH) etc.

Total Outage Hour (OH) = UOH + LH + POH (1)

Where;

UOH = Unplanned Outage hours (Total duration of fault)

LH = Load-shedding hours

POH = Planned outage hours

Hours (H) = Number of days × 24 hours (2)

Service Hours (SH) = H – OH (3)

Mean Time to Failure (MTTF) = SH/NF (4)

Mean Time to Repair (MTTR) = UOH/NF (5)

The mean time between the failure of a component is the sum of the mean time it takes for the component to fail and the mean time required to repair the component. The equation for the mean time between the failure of components is presented in equation 6 below.

Mean Time Between Failure (MTBF) = MTTF + MTTR (6)

Repair Rate (μ) = 1/MTTF (7)

Failure Rate (λ) = 1/MTBF (8)

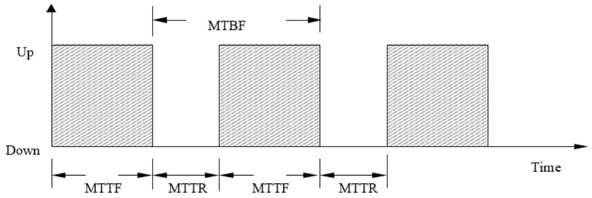


Figure 1: Mean time diagram of a two-state component (Akhikpemelo et al., 2017)

The reliability of each of the components is calculated with the components failure rate as.

$$\mathbf{R(t)} = e^{-\lambda t} = e^{-\frac{t}{MTBF}} \quad (9)$$

This gives R(t) as the reliability of the system component at any time t. The time (t) is given in years.

**Failure Rate Equations for series system**

When there are systems consisting of k components in series and connected in series, the system reliability, Rs, will be given by:

Rs = Rsys = R1. R2. R3…… $R_K$ (10)

where the reliability values for the k components are represented by R1, R2, R3, ……$R_K$, then the system reliability can be determined if failure rates are λ1, λ2..., $\lambda_k$;

$$R_S = e^{-\lambda_1 t} \cdot e^{-\lambda_2 t} \ldots e^{-\lambda_k t} \qquad (11)$$

$$= e^{-(\lambda_1 + \lambda_2 + \cdots \ldots + \lambda_k)t} \qquad (12)$$

The equation for system failure rate $\lambda_S$ can be derived from system reliability $R_S$ as;

$$R_S = e^{-\lambda_S t} \qquad (13)$$

where;

$$\lambda_S = \sum_{i=1}^{n} \lambda_i \qquad (14)$$

and $\lambda_S$ is constant. It should be noted that while component failure rates are constant, the system failure rate is also constant. In other words, when constant failure rate components are used in a series configuration, the system failure rate at any mission time is equal to the steady-state failure rate (Ren et al., 2017). The component failure rate can determine by equation 15If their failure rates are the same, $\lambda_c$, this is given by:

$$\lambda_S = k\lambda_C \qquad (15)$$

Similar to blocks with constant failure rates placed in series, the system failure rate equation for k blocks with non-constant (i.e., time-dependent) failure rates is given by Afsharnia (2017) as:

$$\lambda_S(\mathrm{t}) = \sum_{i=1}^{k} \lambda_i\,(t) \qquad (16)$$

where $\lambda_S(t)$ and $\lambda_i(t)$ are functions of time.

**Failure Rate Equations for parallel systems**

When "**k**" identical constant failure rate component arranged in parallel is considered, the system reliability equations become;

$$R_S = 1 - (\,1 - \; R_C\,)^k \qquad (17)$$

The system reliability is represented by $R_S$ while the reliability of each component is $R_C$. Substituting where $R_C$ is the reliability of each component and $R_S$ is the system reliability. Replacing the formular for component reliability with constant failure rate $\lambda_C$ gives:

$$R_S = 1 - \left(1 - \; e^{-\lambda_C t}\right)^k \qquad (18)$$

**Reliability Block Diagram**

Reliability is the probability that a system performs correctly during a specific time duration (Raza, 2019). Fault tolerance is the ability of a system not to fail even when there are faulty components (Callou et al., 2012). In fault-tolerant systems, reliability provides the probability that a system will function even when there are faulty components (Dialynas & Zafiropoulos, 2003).

The Reliability Block Diagram (RBD) is a diagrammatic method of analysis used to assess the reliability of a complex system based on the logical interaction of failures within a system that is required to sustain system operation (Safeopedia, 2017). The technique was extended to compute availability and maintainability. The RBD structure establishes a logical interaction between the components, defining which combinations of failed and active elements are able to sustain system operation (Afsharnia, 2017). Thus, the system is represented by subsystems or components connected according to their function or reliability relationship (Afsharnia, 2017).

**Two Components in Series**

A series configuration works like a chain which is only as strong as its weakest link. This is a major disadvantage of the series structure, however, with a parallel structure both parts of the system must fail for the system to stop working. This is shown in Figure 2 and the equations needed to evaluate the basic indices are as follows (Akhikpemelo et al., 2017; Afsharnia, 2017).

Figure 2: Series Structure (RBD)

For the two components in series, the average failure rate of the system is given by:

$$\boldsymbol{\lambda_{sys} = \lambda_1 + \lambda_2} \qquad (19)$$

Average failure duration of the system $\mathbf{r_{sys}}$ is given by;

$$r_{sys} = \frac{\lambda_1 r_1 + \lambda_2 r_2 + (\lambda_1 r_1)(\lambda_2 r_2)}{\lambda_{sys}} \approx \frac{\lambda_1 r_1 + \lambda_2 r_2}{\lambda_{sys}} \qquad (20)$$

Average annual outage time of the system is given by;

$$U_{sys} = \lambda_{sys} * r_{sys} \qquad (21)$$

**Two Components in Parallel**

Similarly, in parallel systems, the failure modes of the load point involve overlapping outages, i.e., two or more components must be on the outage at the same time in order to interrupt a load point as shown in Figure 3 The equations used to calculate the indices of the overlapping outage are provided below. They are based on the assumption that the failures are independent, and restoration includes either repair or replacement of affected systems. (Akhikpemelo et al., 2017)

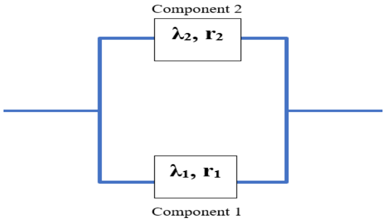


Figure 3: Parallel Structure (RBD)

$$r_{sys} = \frac{\lambda_1 \lambda_2 (r_1 + r_2)/\,8760}{1 + (\lambda_1 r_1 + \lambda_2 r_2)/8760} \approx \frac{\lambda_1 \lambda_2 (r_1 + r_2)}{8760} \qquad (22)$$

$$r_{sys} = \frac{r_1 r_2}{r_1 + r_2} \qquad (23)$$

$$\mathit{Average\ failure\ rate},\ \lambda_{sys} = \sum_i \lambda_i \qquad (24)$$

$$\mathit{Average\ annual\ outage\ timefailure\ rate},\ U_{sys} = \sum_i \lambda_i r_i \qquad (25)$$

$$\mathit{Average\ outage\ time},\ r_{sys} = \frac{U_s}{\lambda_s} = \frac{\sum_i \lambda_i r_i}{\sum_i \lambda_i} \qquad (26)$$

These are adequate for simple radial systems and more extended indices must be used for general distribution systems (mixed radial and meshed systems).

## Methodology

To achieve the aim of this research work, the first work done was to carry out a detailed characterization of the network under study. This was done to determine the behaviour of the key performance parameters MTTF, MTTR, MTBF, system reliability and failure rate.

Details of the characterization of the mobile switching centre network are described below.

### Block Diagram Model of Measurement Setup

The data for this work was obtained from the Human Machine Interface of the Scada panel inside MTN Enugu Switch Energy Centre which is powered on a 24Vdc supply from a DC-DC converter and the 24Vdc supply from the diesel generator (DG) battery. The DC-DC converter is connected to the UPS circuit to ensure data stored on the HMI is always retained. The HMI by default can retain data for 6 months at which stage it purges itself of data on first in first-out basis (FIFO). The HMI has input terminals for the power sources, output terminals for the distribution breakers feeding the Switch prefab rooms (Prefab 01 – Prefab06), feedback control input, alarms and status indication lamps.

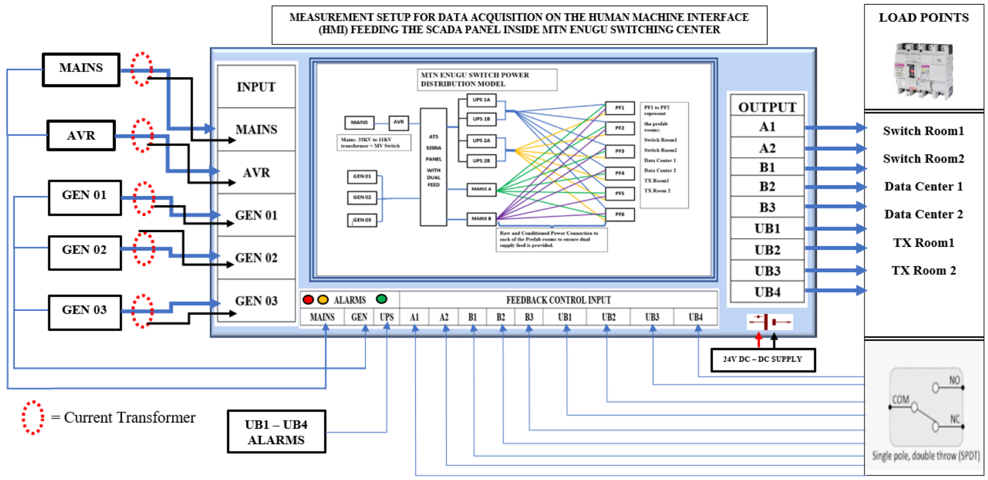


*Figure 4: Block Diagram of Measurement Setup*

The power source input terminals on the HMI have the AC input lines from the transformer, AVR and standby generators. The voltage levels are monitored from the LV distribution panel through the AC input lines while the current monitoring is achieved through the CT (this is coloured red). The CTs are 5A/3200A which is meant to capture the full load current of each of the sources. The distribution breakers feeding the prefab rooms received their close or open command from the HMI output terminals and provide feedback on command execution through normally open (NO) or normally closed (NC) contact in the LV distribution panel to the feedback control input terminals. The Alarm input terminals are wired to ensure supervisory functions on all the power sources, distribution breakers and UPS and report through the alarm indication lamp status. The voltage level per phase, current per phase, power per phase and alarms for each of the distribution feeder breakers can be read off from the HMI. The HMI can be queried to provide data on each breaker failure time and failure clear time and can support 6 months of data enquiry. For this test, data was collected for a one-year period to accommodate and monitor the impact of the various seasons on the availability/service hours of the breakers. The measurement setup is as shown above in Figure 4. The experiments were carried out jointly by myself, the field technician in the Switch centre and his supervisor. My role in the experiment was to provide guidance on how I wanted the system set up to be so I can obtain relevant data. I also ensured the HMI reports were calibrated to suit the measurement template – I expanded the search criteria from weekly to see daily performance reports and on the daily, I also expanded to see the hours of the day the breaker failure occurred. The weekly service hours availability of the breakers over 8760hrs of the year was reduced down to weekly figures represented in percentage to show the service availability of each breaker in 168hrs of the week. The raw data for the weekly service availability report for the switch passive infrastructure – Power and Cooling is shown in Appendix I.

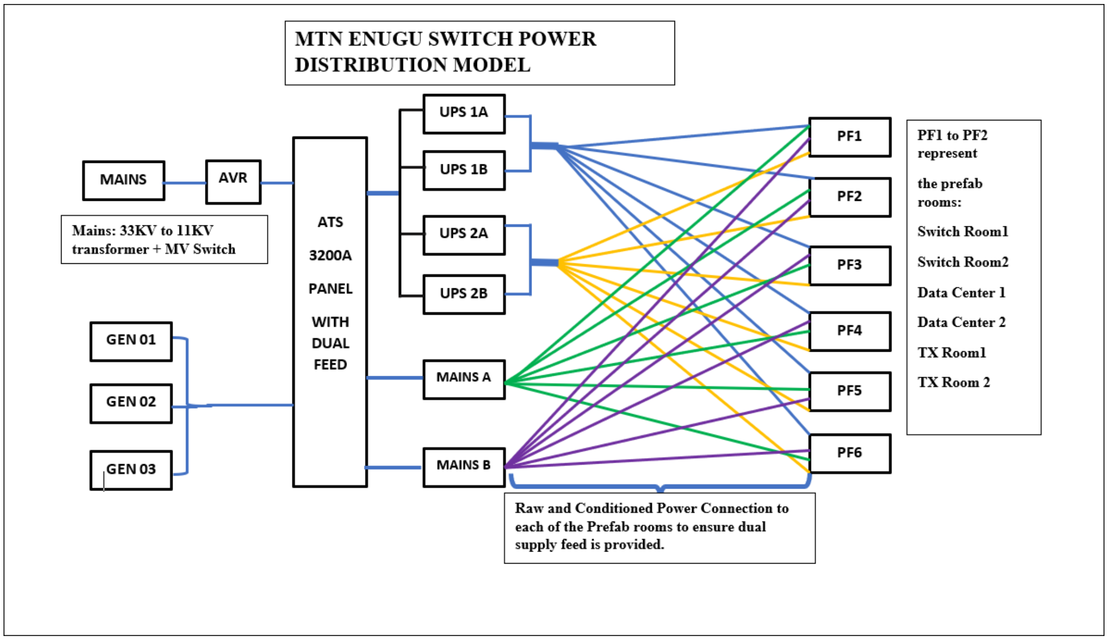


***Figure 5: Power Distribution Flow Diagram***

MTN Enugu mobile switching centre is located at Zoo estate, normally referred to as Ekulu East estate GRA. In this work, we shall characterize the power infrastructure and distribution network. The power distribution network comprises an overhead 33kV line from the Thinkers Corner injection substation. The metering infrastructure – the CVTs and the CT are located at the HT pole and this supply feeds an MV switch gear which provides protection through its relays on the HV side. At the load points, a 1.5MVA transformer further reduces the voltage on the MV panel from 33kV 11kV which is fed to another 1.5MVA transformer which reduces the voltage further to 415V to provide the last-kilometre connection through 415V feeders on the LV panel to the AVR and 500kVa power factor correction equipment. The output of the AVR feeds an automatic transfer switch which is capable of selecting from three standby energy sources – 3 X 1.5MVA generators to provide the required redundancy of 3N + 1 necessary to guarantee stable supply. The 3200A ATS panel is properly dimensioned to provide dual power supply feed for all the power distribution boards for the six prefab rooms and all connected equipment is installed with dual power sources so that in the event of a supply input failure, the second supply input is able to provide enough power to support the switching centre energy requirement. Part of the steady state strategy is to ensure that the load at any time on each power source does not exceed 65% utilization so that recovery from failure is seamless because of the battery energy storage systems that need to recharge and also because the compressors in the HVACs will run a much longer period to overcome the heat load from the equipment. In the Switching centre, there are two data centres for the servers and routers, two equipment rooms for the BSCs and RNCs and two transmission rooms. Below is the installed power capacity of the passive equipment in each of the prefab rooms.

**Table 1: Power Equipment Distribution in MTN Enugu Switch**

| EQUIPMENT LOCATION | PREFAB | COOLING |
|---|---|---|
| **SWITCH ROOM1** | Prefab01 | 25KW X 6 |
| **SWITCH ROOM2** | Prefab02 | 25KW X 6 |
| **DATA CENTRE1** | Prefab 03 | 50KW X 6 |
| **DATA CENTRE2** | Prefab 04 | 50KW X 6 |

| | | |
|---|---|---|
| **TRANSMISSION ROOM 1** | Prefab 05 | 25KW X 6 |
| **TRANSMISSION ROOM 2** | Prefab 06 | 25KW X 6 |

### Development of a Model of the Cooling Reliability of the Evaluated Network

In order to get an expression that represents the behaviour of the system under study and to understand and learn about the system we want to improve, a model of the cooling reliability of the evaluated network was developed to show the different operational scenarios, use cases and how the system will function or react in different environments. The data required to develop the reliability model to show the failure rate of the mobile switching centre cooling infrastructure was obtained from the resident switch operator's hourly log book and crosschecked with the Human Machine Interface Console data. The results obtained are the outage rates of the LV distribution breakers feeding each of the prefab rooms. These include unplanned outages, occurrence and service availability of these breakers within the period of study. This shows the service locations, power availability, number of failures per year, service hours and outage hours. The MTTF, MTTR, MTBF, failure rate and repair rate were derived from the log. It was also observed that there was no provision in the log to separate the planned outages which were for corrective maintenance for the period in review as records from the available data only took note of the overall outage duration. 20% of the overall outage duration was allocated to unplanned outages to estimate the MTTR values of each service location. Data is for one year period. Below are the average readings obtained for each of the prefab rooms during a power changeover.

### Evaluation of Reliability Block Diagram of the Evaluated Network

Data obtained was evaluated to determine the failure rate, MTBF and reliability of all the cooling equipment (HVACs) in all the prefab rooms. The combined reliability of each of the prefab rooms was evaluated using reliability block diagrams (RBD).

### Cooling Reliability Evaluation

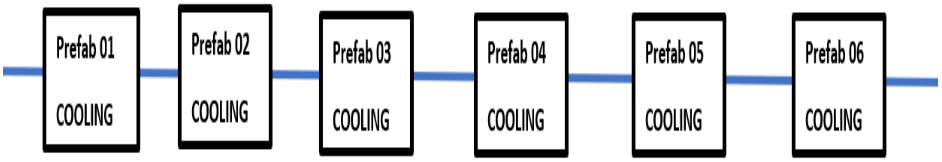


**Figure 6: Cooling Reliability Block Diagram for MTN Enugu Switch**

Above is the RBD for prefab cooling in MTN Enugu Switching Centre. The model in Figure 6 above comprises the sub-model below which is broken down into the HVAC cooling configuration in each of the prefab rooms. Each prefab room has 6 x 45KW HVAC installed with four units working and two units on redundant standby (4N+2) configuration.

We will calculate the combined cooling reliability of each of the prefabs using the topology

Solving for Prefab 01 gives:

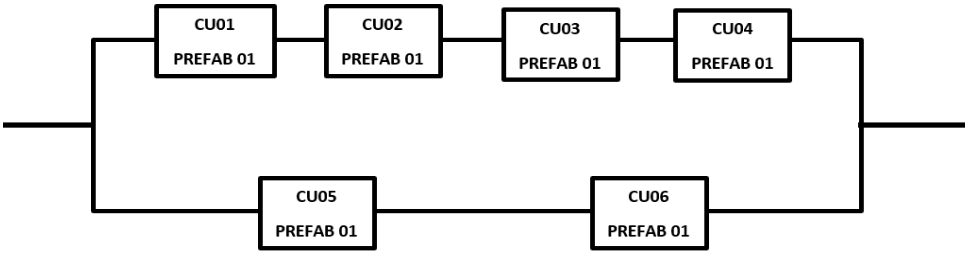


**Figure 7: Cooling Reliability Block Diagram for Each Prefab Room**

In prefab 01, there are four cooling units (CU01, CU02, CU03 & CU04). To determine the RBD series branch 1, we refer to equation (10) and solving for Rsys, gives:

$R_{sys}$ = RCU1 * RCU2 * RCU3 * RCU4; where CU1 = 0.8438, CU2 = 0.9186, CU3 = 0.9186, CU4 = 0.8438.

$R_{sys}$ = 0.8438 * 0.9186 * 0.9186 * 0.8438

$R_{sys}$ = 0.6008,

Similarly, solving for branch 2 (CU05 & CU06), gives:

$R_{sys}$ = RCU5 * RCU6; where CU5 = 0.8438, CU6 = 0.9186

$R_{sys}$ = 0.8438 * 0.9186

$R_{sys}$ = 0.7751

Combining branch 1 & 2 for prefab 01, gives:

$R_s$ = 1 – [(1 – R1) * (1 – R2)],

Where $R_1$ and $R_2$ = Unavailability of branch 1 & 2 of prefab 01 cooling, gives:

R1 = (1 – 0.6008) = 0.3992

R2 = (1 – 0.7751) = 0.2249

Substituting values, we have:

Rsys = 1 – (0.3992 * 0.2249),

Rsys = 1 – 0.0897

Rsys = 0.9103

Rsys = 91.03%... this is the equivalent reliability of the RBD of prefab 01.

Solving for Prefab 02, gives:

In prefab 02, there are four cooling units (CU01, CU02, CU03 & CU04). To determine the RBD series branch 1, we refer to equation (10) and solving for Rsys, gives:

Rsys = RCU1 * RCU2 * RCU3 * RCU4; where CU1 = 0.8438, CU2 = 0.9186, CU3 = 0.8438, CU4 = 0.8438.

$R_{sys}$ = 0.8438 * 0.9186 * 0.8438 * 0.8438

$R_{sys}$ = 0.5519,

Similarly, solving for branch 2 (CU05 & CU06), gives:

$R_{sys}$ = RCU5 * RCU6; where CU5 = 0.8438, CU6 = 0.8438

$R_{sys}$ = 0.8438 * 0.8438

$R_{sys}$ = 0.7119

Combining branch 1 & 2 for prefab 02, gives:

$R_s = 1 – [(1 – R1) * (1 – R2)]$,

Where R1 and R2 equal the unavailability values of branches 1 and 2 of prefab 02 cooling, solving gives:

$R_1 = (1 – 0.5519) = 0.4481$

$R_2 = (1 – 0.7719) = 0.2281$

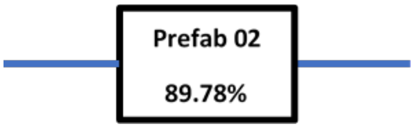
Substituting values, we have:

$R_{sys} = 1 – (0.4481 * 0.2281)$,

$R_{sys} = 1 – 0.1022$

$R_{sys} = 0.8978$

$R_{sys} = 89.78\%$... this is the equivalent reliability of the RBD of prefab 02.



Solving for Prefab 03, gives;

In prefab 03, there are four cooling units (CU01, CU02, CU03 & CU04). To determine the RBD series branch 1, we refer to equation (10) and solving for Rsys, gives:

$R_{sys} = RCU1 * RCU2 * RCU3 * RCU4$; where CU1 = 0.8438, CU2 = 0.8438, CU3 = 0.9186, CU4 = 0.9186.

$R_{sys} = 0.8438 * 0.8438 * 0.9186 * 0.9186$

$R_{sys} = 0.6008$,

Similarly, solving for branch 2 (CU05 & CU06), gives:

$R_{sys} = RCU5 * RCU6$; where CU5 = 0.9186, CU6 = 0.9186

$R_{sys} = 0.9186 * 0.9186$

$R_{sys} = 0.8438$,

Combining branch 1 & 2 for prefab 03, gives:

$R_s = 1 – [(1 – R_1) * (1 – R_2)]$,

Where $R_1$ and $R_2$ = Unavailability of branch 1 & 2 of prefab 03 cooling, gives:

$R_1 = (1 – 0.6008) = 0.3992$

$R_2 = (1 – 0.8438) = 0.1562$

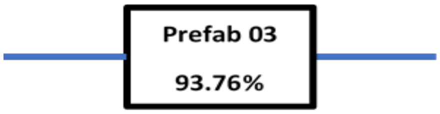
Substituting values, we have:

$R_{sys} = 1 – (0.3992 * 0.1562)$,

$= 1 – 0.0624$

$= 0.9376$

$R_{sys} = 93.76\%$... this is the equivalent reliability of the RBD of prefab 03.



Solving for Prefab 04, gives:

In prefab 04, there are four cooling units (CU01, CU02, CU03 & CU04). To determine the RBD series branch 1, we refer to equation (10) and solving for Rsys, gives:

Rsys = RCU1 * RCU2 * RCU3 * RCU4; where CU1 = 0.8438, CU2 = 0.9186, CU3 = 0.9186, CU4 = 0.8438.

$R_{sys}$ = 0.8438 * 0.9186 * 0.9186 * 0.8438

$R_{sys}$ = 0.6008.

Similarly, solving for branch 2 (CU05 & CU06), gives:

$R_{sys}$ = RCU5 * RCU6; where CU5 = 0.9186, CU6 = 0.8438,

$R_{sys}$ = 0.9186 * 0.8438

$R_{sys}$ = 0.7751

Combining branch 1 & 2 for prefab 04, gives:

$R_s$ = 1 – [(1 – R1) * (1 – R2)],

Where $R_1$ and $R_2$ = Unavailability of branch 1 & 2 of prefab 04 cooling, gives:

$R_1$ = (1 – 0.6008) = 0.3992

$R_2$ = (1 – 0.7751) = 0.2249

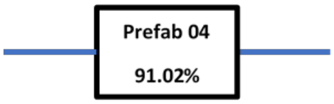
Substituting values, we have:

$R_{sys}$ = 1 – (0.3992 * 0.2249),

$R_{sys}$ = 1 – 0.0898

$R_{sys}$ = 0.9102

$R_{sys}$ = 91.02%, is the equivalent reliability of prefab 04 RBD.



Solving for Prefab 05, gives:

In prefab 05, there are four cooling units (CU01, CU02, CU03 & CU04). To determine the RBD series branch 1, we refer to equation (10) and solving for Rsys, gives:

$R_{sys}$ = RCU1 * RCU2 * RCU3 * RCU4; where CU1 = 0.9186, CU2 = 0.8438, CU3 = 0.9186, CU4 = 0.8438.

$R_{sys}$ = 0.9186 * 0.8438 * 0.9186 * 0.8438

$R_{sys}$ = 0.6008,

Similarly, solving for branch 2 (CU05 & CU06), gives:

$R_{sys}$ = RCU5 * RCU6; where CU5 = 0.9186, CU6 = 0.8438,

$R_{sys}$ = 0.9186 * 0.8438

$R_{sys}$ = 0.7751

Combining branch 1 & 2 for prefab 05, gives:

Rs = 1 – ((1 – R1) * (1 – R2)),

R1 and R2 are the Unavailability of branch 1 & 2 in prefab 05 cooling. Solving gives;

R1 = (1 – 0.6008) = 0.3992

R2 = (1 – 0.7751) = 0.2249

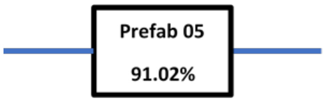
Substituting values, we have:

Rsys = 1 – (0.3992 * 0.2249),

Rsys = 1 – 0.0898

$R_{sys}$ = 0.9102

$R_{sys}$ = 91.02%, this is the equivalent reliability of the RBD of prefab 05.



Solving for Prefab 06, gives:

In prefab 06, there are four cooling units (CU01, CU02, CU03 & CU04). To determine the RBD series branch 1, we refer to equation (10) and solving for Rsys, gives:

$R_{sys}$ = RCU1 * RCU2 * RCU3 * RCU4; where CU1 = 0.9186, CU2 = 0.8438, CU3 = 0.9186, CU4 = 0.9186.

$R_{sys}$ = 0.9186 * 0.8438 * 0.9186 * 0.9186

$R_{sys}$ = 0.6541,

Similarly, solving for branch 2 (CU05 & CU06), gives:

$R_{sys}$ = RCU5 * RCU6; where CU5 = 0.8438, CU6 = 0.9186,

$R_{sys}$ = 0.8438* 0.9186

$R_{sys}$ = 0.7751

Combining branch 1 & 2 for prefab 06, gives:

Rs = 1 – ((1 – R1) * (1 – R2)),

Where R1 and R2 = Unavailability of branch 1 & 2 of prefab 06 cooling, gives:

R1 = (1 – 0.6541) = 0.3459

R2 = (1 – 0.7751) = 0.2249

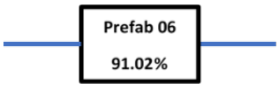
Substituting values, we have:

Rsys = 1 – (0.3459 * 0.2249),

Rsys = 1 – 0.0778

Rsys = 0.9222

Rsys = 92.22%, this is the equivalent reliability of the RBD of prefab 06.



**Data Presentation**

The Combined cooling reliabilities of each of the prefab rooms which we have evaluated above for prefabs 01 to prefab 06, gives us;

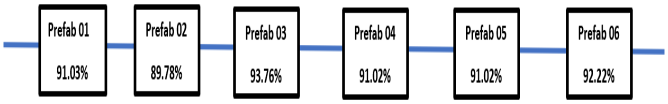


Figure 8: Result of the evaluation of the prefab cooling reliability

Hence when we solve, gives:

Rsys = RPFB01 * RPFB02 * RPFB03* RPFB04 * RPFB05 * RPFB06;

Where;

PFB01 = 0.9103,

PFB02 = 0.8978,

PFB03 = 0.9376,

PFB04 = 0.9102,

PFB05 = 0.9102,

PFB06 = 0.9222

Rsys = 0.9103 * 0.8978 * 0.9376 * 0.9102 * 0.9102 * 0.9222

Rsys = 0.5854.

**Table 2: Reliability Model and Failure Rate of MTN Enugu Switch Cooling Infrastructure**

| S/NO. | INFRA TYPE | LOCATION | RELIABILITY | FAILURE RATE | MTBF |
|---|---|---|---|---|---|
| **1** | COOLING | PREFAB 01 | 91.03% | 0.000126318 | 7,917 |
| | | PREFAB 02 | 89.78% | 0.000144903 | 6,901 |
| | | PREFAB 03 | 93.76% | 0.000086601 | 11,547 |
| | | PREFAB 04 | 91.02% | 0.000126466 | 7,907 |
| | | PREFAB 05 | 91.02% | 0.000126466 | 7,907 |
| | | PREFAB 06 | 92.22% | 0.000108860 | 9,186 |
| **2** | COMBINED COOLING | PREFABs (01 – 06) | 58.54% | 0.000719704 | 1,389 |

**Conclusion**

The cooling infrastructure RBD analysis of section 3 shows that the combined reliability, MTBF and failure rate **(λ)** of the combined cooling reliability, MTBF and failure rate (λ), is 58.54%, 1389hrs and 0.000719704 respectively.

Further analysis shows the reliability of the cooling infrastructure at 250hrs is 83.53% and reduces further to 58.54% after 744hrs. This result is far below the data centre cooling reliability requirement of 99.999% and suggests that there is a 58.54% chance that the cooling units in the prefabs rooms will continue to work optimally after a period of 744hrs (1-month cycle) if preventive maintenance is not done.

Also, we can see from the RBD the cooling units with the highest failure rate in each of the prefab rooms so that adequate preventive maintenance programs can be put in place to ensure surprise failures are averted.

With the aid of the RBD models of each of the prefab rooms and the failure rate of each of the cooling units, optimal decisions on reliability initiatives and programs can be made on the preventive maintenance scheduling for the system and also will help to plan the replacement period for already deteriorating systems using the failure data (when reliability improvement is not achieved after even scheduled preventive maintenance).

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**APPENDIX I**: MTTR, MTTF, MTBF and System Failure Rate (λ) for the HVACs in MTN Switch prefab rooms

| S/NO. | NAME | SERVICE LOCATION | NUMBER OF FAULTS | SERVICE HOURS /ANNUM | OUTAGE HOURS | AVAILABILITY BASED ON SERVICE HOURS | MTTF | MTTR | MTBF | SYSTEM FAILURE RATE (Λ) | SYSTEM REPAIR RATE (M) | RELIABILITY FOR 1YR (8760HRS) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | A1 | UTILITY SUPPLY | 2 | 8716 | 44 | 99.50% | 4358 | 22 | 4380 | 0.0002283 | 0.05 | 84.38% |
| **2** | A2 | AVR | 1 | 8752 | 8 | 99.91% | 8752 | 8 | 8760 | 0.0001142 | 0.13 | 91.86% |
| **3** | B1 | GEN 01 | 2 | 8698 | 62 | 99.29% | 4349 | 31 | 4380 | 0.0002283 | 0.03 | 84.38% |
| **4** | B2 | GEN 02 | 1 | 8758 | 2 | 99.98% | 8758 | 2 | 8760 | 0.0001142 | 0.5 | 91.86% |
| **5** | B3 | GEN 03 | 1 | 8758 | 2 | 99.98% | 8758 | 2 | 8760 | 0.0001142 | 0.5 | 91.86% |
| **6** | CU1A | PREFAB 01 | 2 | 8759 | 1 | 99.99% | 4379.5 | 0.5 | 4380 | 0.0002283 | 2 | 84.38% |
| **7** | CU1B | | 1 | 8759 | 1 | 99.99% | 8759 | 1 | 8760 | 0.0001142 | 1 | 91.86% |
| **8** | CU1C | | 1 | 8759 | 1 | 99.99% | 8759 | 1 | 8760 | 0.0001142 | 1 | 91.86% |
| **9** | CU1D | | 2 | 8759 | 1 | 99.99% | 4379.5 | 0.5 | 4380 | 0.0002283 | 2 | 84.38% |
| **10** | CU1E | | 2 | 8752 | 8 | 99.91% | 4376 | 4 | 4380 | 0.0002283 | 0.25 | 84.38% |
| **11** | CU1F | | 1 | 8752 | 8 | 99.91% | 8752 | 8 | 8760 | 0.0001142 | 0.13 | 91.86% |
| **12** | CU2A | PREFAB 02 | 2 | 8759 | 1 | 99.99% | 4379.5 | 0.5 | 4380 | 0.0002283 | 2 | 84.38% |
| **13** | CU2B | | 1 | 8759 | 1 | 99.99% | 8759 | 1 | 8760 | 0.0001142 | 1 | 91.86% |
| **14** | CU2C | | 2 | 8759 | 1 | 99.99% | 4379.5 | 0.5 | 4380 | 0.0002283 | 2 | 84.38% |
| **15** | CU2D | | 2 | 8759 | 1 | 99.99% | 4379.5 | 0.5 | 4380 | 0.0002283 | 2 | 84.38% |
| **16** | CU2E | | 2 | 8759 | 1 | 99.99% | 4379.5 | 0.5 | 4380 | 0.0002283 | 2 | 84.38% |
| **17** | CU2F | | 2 | 8759 | 1 | 99.99% | 4379.5 | 0.5 | 4380 | 0.0002283 | 2 | 84.38% |
| **18** | CU3A | PREFAB 03 | 2 | 8759 | 1 | 99.99% | 4379.5 | 0.5 | 4380 | 0.0002283 | 2 | 84.38% |
| **19** | CU3B | | 2 | 8759 | 1 | 99.99% | 4379.5 | 0.5 | 4380 | 0.0002283 | 2 | 84.38% |
| **20** | CU3C | | 1 | 8759 | 1 | 99.99% | 8759 | 1 | 8760 | 0.0001142 | 1 | 91.86% |
| **21** | CU3D | | 1 | 8759 | 1 | 99.99% | 8759 | 1 | 8760 | 0.0001142 | 1 | 91.86% |
| **22** | CU3E | | 1 | 8752 | 8 | 99.91% | 8752 | 8 | 8760 | 0.0001142 | 0.13 | 91.86% |
| **23** | CU3F | | 1 | 8752 | 8 | 99.91% | 8752 | 8 | 8760 | 0.0001142 | 0.13 | 91.86% |
| **24** | CU4A | PREFAB 04 | 2 | 8759 | 1 | 99.99% | 4379.5 | 0.5 | 4380 | 0.0002283 | 2 | 84.38% |
| **25** | CU4B | | 1 | 8759 | 1 | 99.99% | 8759 | 1 | 8760 | 0.0001142 | 1 | 91.86% |
| **26** | CU4C | | 1 | 8759 | 1 | 99.99% | 8759 | 1 | 8760 | 0.0001142 | 1 | 91.86% |
| **27** | CU4D | | 2 | 8759 | 1 | 99.99% | 4379.5 | 0.5 | 4380 | 0.0002283 | 2 | 84.38% |
| **28** | CU4E | | 1 | 8752 | 8 | 99.91% | 8752 | 8 | 8760 | 0.0001142 | 0.13 | 91.86% |
| **29** | CU4F | | 2 | 8752 | 8 | 99.91% | 4376 | 4 | 4380 | 0.0002283 | 0.25 | 84.38% |
| **30** | CU5A | PREFAB 05 | 1 | 8759 | 1 | 99.99% | 8759 | 1 | 8760 | 0.0001142 | 1 | 91.86% |
| **31** | CU5B | | 2 | 8759 | 1 | 99.99% | 4379.5 | 0.5 | 4380 | 0.0002283 | 2 | 84.38% |
| **32** | CU5C | | 1 | 8759 | 1 | 99.99% | 8759 | 1 | 8760 | 0.0001142 | 1 | 91.86% |
| **33** | CU5D | | 2 | 8759 | 1 | 99.99% | 4379.5 | 0.5 | 4380 | 0.0002283 | 2 | 84.38% |
| **34** | CU5E | | 1 | 8759 | 1 | 99.99% | 8759 | 1 | 8760 | 0.0001142 | 1 | 91.86% |
| **35** | CU5F | | 2 | 8759 | 1 | 99.99% | 4379.5 | 0.5 | 4380 | 0.0002283 | 2 | 84.38% |
| **36** | CU6A | PREFAB 06 | 1 | 8759 | 1 | 99.99% | 8759 | 1 | 8760 | 0.0001142 | 1 | 91.86% |
| **37** | CU6B | | 2 | 8759 | 1 | 99.99% | 4379.5 | 0.5 | 4380 | 0.0002283 | 2 | 84.38% |
| **38** | CU6C | | 1 | 8759 | 1 | 99.99% | 8759 | 1 | 8760 | 0.0001142 | 1 | 91.86% |
| **39** | CU6D | | 1 | 8759 | 1 | 99.99% | 8759 | 1 | 8760 | 0.0001142 | 1 | 91.86% |
| **40** | CU6E | | 2 | 8759 | 1 | 99.99% | 4379.5 | 0.5 | 4380 | 0.0002283 | 2 | 84.38% |
| **41** | CU6F | | 1 | 8752 | 8 | 99.91% | 8752 | 8 | 8760 | 0.0001142 | 0.13 | 91.86% |