Performance Evaluation of a Complex Reverse Osmosis Machine System in Water Purification using Reliability, Availability, Maintainability and Dependability Analysis

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Abstract

Today, reverse osmosis (RO) is a critical technique in the production of fresh water all over the world. As a result, downtimes due to repairing operations (after breakdowns, membrane blockage, pressure losses, etc.) or preventative maintenance (cleaning of membranes, component replacements, etc.) must be kept to a minimum in duration and frequency to guarantee optimum availability. Indeed, enhancing the availability (or dependability) of the RO plant as a whole system leads to a significant decrease in operating and maintenance expenses. We look at a recursive technique for reliability, availability, maintainability, and dependability in this study (RAMD. In addition, the efficacy of a RO unit, mean time to failure (MTTF), mean time to repair (MTTR), and dependability ratio were evaluated. The primary goal is economic optimization. For the method's validation, we utilized data from a RO unit that had a repair rate and a failure rate during a one-year period. It was demonstrated that all subsystems (pretreatment, dosage, etc.) had high availability. The high-pressure pump has a somewhat lower availability. For example, 0.59113 was the lowest availability for all subsystems, and it is for the RO membrane, which is where the majority of the purifications take place. A sensitivity analysis was performed to identify the essential components for the RO plant's availability. The collected findings demonstrate that the availability, reliability, dependability, and maintainability of the high-pressure pump have a significant impact on the overall system availability. As a result, special care should be given in the selection and maintenance of the high-pressure pump.

Keywords: Reverse osmosis, reliability, failure rate, repair rate.

I. Introduction

Water scarcity is worsening as a result of globalization. The water cycle is being disrupted as a result of the world's significant changes in climatic pattern, Muhammad F.I. [1]. Groundwater, which is either depleted to a certain level or polluted, is a less expensive and more reliable supply of water.

Polluted water may contain biological or inorganic materials as residuals. S.L. Brown et al. [2]. M. Badruzzaman. In 2019 et al. [3] investigated the selection of pretreatment methods for seawater reverse osmosis facilities. F. Saffarimiandoab et al. [4] conducted study on the biofouling behavior of zwitterionic silane covered reverse osmosis membranes contaminated by marine microorganisms. Evita A. et al. [5] conducted the study named a strategy plan for the reuse of treated municipal wastewater for agricultural irrigation on the island of CreteSlvia C Oliveira and Marcos Von Sperling [6] created a reliability study for wastewater treatment plants. Slvia C Oliveira and Marcos Von Sperling did research on reverse osmosis difficulties such as pressure drop, mass transfer, turbulence, and unsteadiness [7Seawater pretreatment for reverse osmosis: Chemistry, pollutants, and coagulation was investigated by James K. Edzwald and Johannes Haarhoff [8]. M.F. Idrees [9] also works with the Performance Analysis and Treatment Technologies of a Reverse Osmosis Plan. C. Li, S. Besarati, and colleagues [10] conducted research on reverse osmosis desalination powered by a low temperature supercritical organic Rankine cycle a few years agoAutomation and dependability are critical components of every advanced reverse osmosis plant in order to fulfill environmental and economic criteria [11]. [12] Developed a computational model based on diffusion and convection transport mechanisms and the concentration polarization concept to predict the performance of a RO membrane using different feed water concentrations, feed flow rates, feed water pressures, membrane specifications, and feed water properties. [13] conducted a study of the concepts and categorization of membrane distillation, with an emphasis on the variables influencing it and ways to improving its efficacy. [14] created a model with five input factors (feed temperature, feed total dissolved solids (TDS), trans-membrane pressure (TMP), feed flow rate, and time) and two output parameters (permeate TDS and flow rate) to estimate the performance of a saltwater reverse osmosis (SWRO) desalination plant It was then used to simulate feed water temperature. [15] compared two hollow fiber module designs (inside/out and outside/in). [16] Experiments were conducted using pure water and NaCl solutions ranging from 15 g/L to 300 g/L, as well as two different fiber materials and structures. Vacuum membrane distillation (VMD) is a method of desalinating saltwater. The two designs were evaluated in terms of pure water permeability and global heat transfer coefficient. It is described how hydrodynamics affects global heat and mass transport coefficients. [17] Investigated the chemical profile, antioxidant and anti-obesity effects of concentrated fractions derived from micro-filtered OMW processed by direct contact membrane distillation (DCMD). Some phenols selected as phytochemical indicators were quantified using ultrahigh performance liquid chromatography (UHPLC). [18] A sequential Direct Contact Membrane Distillation (DCMD) and a Reverse Osmosis (RO) hybrid membrane system were used to treat the pollutants found in olive mill wastewater (total organic carbon (TOC), dissolved organic carbon (DOC), total phosphorus (TP), total nitrogen (TN), and total polyphenols. The effects of permeate flux and pressures on pollutant parameter removals were also investigated. Freshwater shortage has been identified as one of the major issues that humans must solve in the twenty-first century. [19] Investigated how an environmentally friendly, cost-effective, and energy-efficient membrane distillation (MD) process can reduce pollution caused by industrial and domestic wastes. RO is a technique that separates and removes dissolved solids, organics, pyrogens, submicron colloidal debris, color, nitrate, and bacteria from water using semi-permeable spiral wound membranes. Under pressure, feed water is supplied via a semipermeable membrane, where water penetrates the membrane's minute holes and is delivered as filtered water known as permeate water [20]. [21] Investigated different reliability metrics of STP generators using the RAMD method at the component level. For all generator subsystems, mathematical models based on the Markovian birth death process have been developed. These models are extremely useful in analyzing generator reliability, maintainability, and availability. Many years ago, M. D. and Hajeeh Chaudhuri [22] investigated the reliability and availability of reverse osmosis RAMD analysis of complex system is highly beneficial in identifying feasible design modifications for reliability, availability, maintainability, and dependability (RAMD). These changes are necessary to improve the system's dependability, mean time between failures, and availability. The enactment of the industrial system

is dependent on the legislation of the components Monika S. and Ashish K. [26].
Our motivation for exploring the reverse osmosis machine system stems from a serious issue that the water purification industries are encountering due to machine system subsystem failure. And the resulting slow progress in technological advancement in water purification, as well as its importance in the lives of people all over the world Industries are striving hard to keep up with the increasing complexity of machine systems. From the finding of the paper, RAMD analysis used to test the strength, efficiency, and performance improvement of the RO system. Where strength, efficiency and performance improvement of the RO system are determined, the users will be able to serve the cost of medical treatment due to un-pure water. Save from aquatic pollutants. The work is divided into four pieces, including the current introduction. RAMD indices for subsystems are commented on in the second section. The third portion included system description and numerous important definitions; notations are included. Section 4 includes RAMD analysis. Section 5 is devoted to the results' conclusion and implications.

II. RAMD indices for subsystems

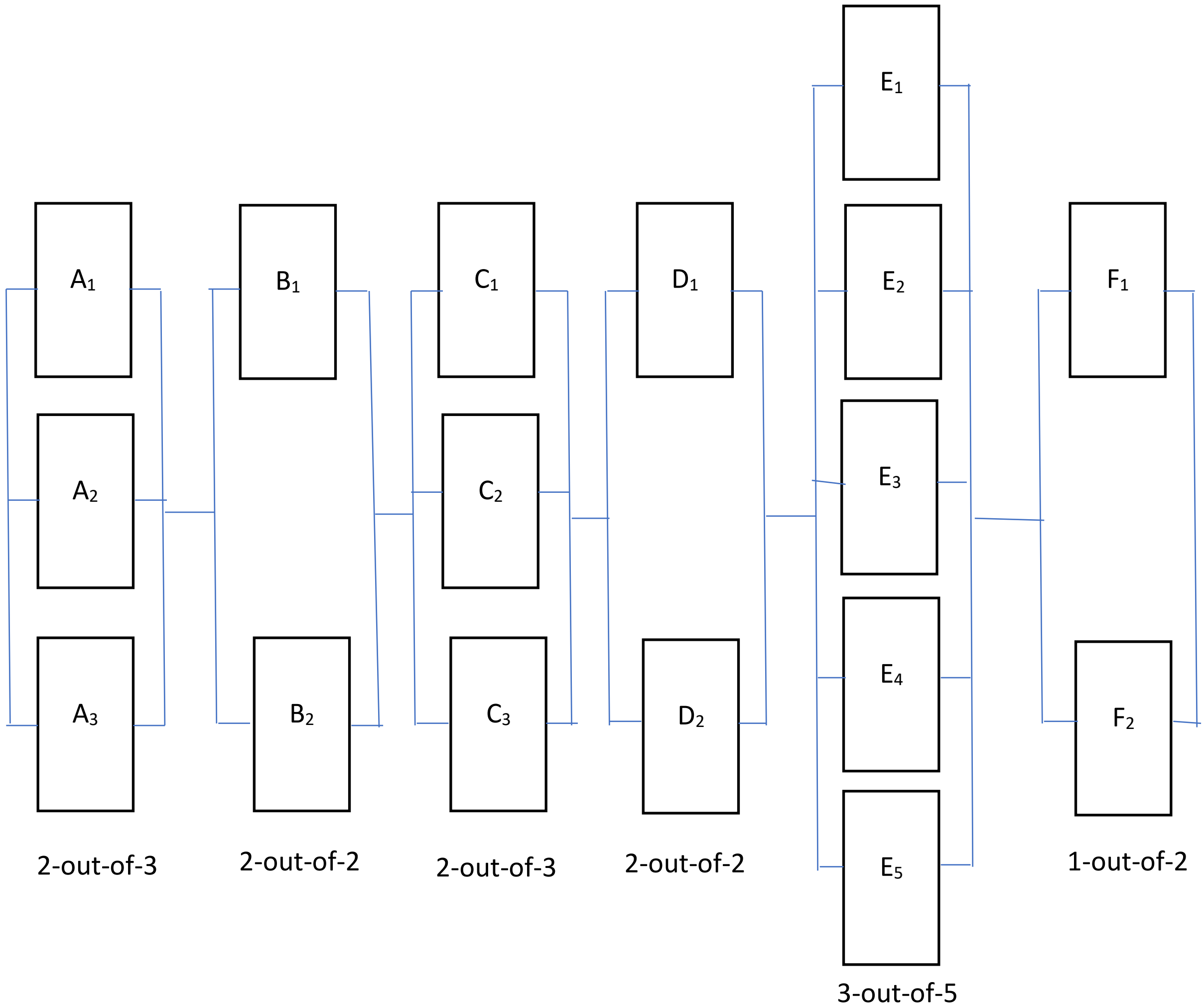
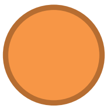
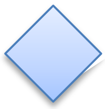


Figure 1: *Block diagram for the RO series-parallel system*

Notations and their meaning


: Represent the system in full capacity state


: Represent the system in reduced but operational state


: Represent the system in failed state

Represent the initial state of the system working in full capacity state.

P_1 : Represent the state in which one parallel unit is failed
P_2 : Represent the state in which two parallel unit is failed
P_3 : Represent the state in which three parallel unit is failed
$K_i \;\; i=i,2,\dots,6$ Represent the failure rates subsystems
$\xi_j \;\; j=1,2,\dots,6$ Represent the repair rates subsystems
$P_x(t)$ Probability to remain at xth state at time t
$\frac{d}{dt}P_x(t)$, x= 0,1,2,3. Represent the derivative with respect to time t
$A_i, \; i=1,2,3$ Units in the subsystem 1.
$B_j, \; j=1,2$ Units from subsystem 2
$C_k, \; k=1,2,3$ Units from subsystem 3
$D_n, \; n=1,2$ Units from subsystem 4
$E_m, \; m=1,2,3,4,5$ Units from subsystem 5
$F_x, \; x=1,2$ Units from subsystem 6.

RAMD indices for subsystem 1 (raw water tank)

Raw water tank**:** Raw water tanks are used to store raw water temporarily until it is treated. This adaptable tank may be folded entirely and compactly for travel. Because the tank is pop-up, no rods or poles are required. Two out of three parallel subsystem, failure of any two can cause the failure of the entire system.

$$\frac{d}{dt}P_0(t) = -2K_1P_0 + \xi_1 P_1 K_1 \quad (1)$$

$$\frac{d}{dt}P_1(t) = -(K_1 + \xi_1)P_1 + 2K_1P_0 + \xi_1 P_2 \quad (2)$$

$$\frac{d}{dt}P_2(t) = -\xi_1 P_2 + K_1P_1 \quad (3)$$

Under steady state, the state's probabilities in equation (1) - (3) are as follows

$$P_1 = \frac{2K_1}{\xi_1}P_0 \quad (4)$$

$$P_2 = \frac{2K_1^2\xi_1}{\xi_1^2}P_0 \quad (5)$$

Using normalization condition

$$P_0 + P_1 + P_2 = 1 \quad (6)$$

Substituting (4) and (5) into (6) we have

$$P_0 + \frac{2K_1}{\xi_1}P_0 + \frac{2K_1^2\xi_1}{\xi_1^2}P_0 = 1$$

$$P_0 = \frac{\xi_1}{\xi_1 + 2K_1^2 + 2K_1} \quad (7)$$

Availability = $A_{s1} = \left(\frac{0.07}{0.08005}\right) = 0.87445$

Table 4 contains important device output metrics that have been extracted.
Dependability of subsystem 1

$$D_{min} = 1 - (\frac{1}{d-1})(e^{-\frac{lnd}{d-1}} - e^{-\frac{d\ln d}{d-1}}) \quad (8)$$

$$d = \frac{\xi}{K} = \frac{MTBF}{MTTR} \quad (9)$$

$d_1 = \frac{\xi_1}{K_1} = \frac{0.07}{0.005} = 14.00$

$D_{\min\,(s1)} = 1 - (\frac{1}{14-1})(e^{-\frac{2.6391}{13}} - e^{\frac{36.9468}{13}})$

$D_{\min\,(s1)} = 1 - 0.05831$

The reliability of subsystem 1

$$R_{s1}(t) = e^{-0.005t} \quad (10)$$

Maintainability of subsystem 1

$$M_{s1}(t) = 1 - e^{-0.07t} \quad (11)$$

Other performance measures of system effectiveness of subsystem 1 are as follows
MTBF = 200.00
MTTR = 14.286
Dependability ratio = 14.00

RAMD indices for subsystem 2 (sand filter)

Sand Filter: George Solt CEng, F. IChem E. [23] Sand filters are widely used in water purification and remove suspended matter by a completely different mechanism. Instead of the water passing through small orifices through which particles cannot pass, it runs through a bed of filter medium, typically 0.75 mm sand 750 mm deep. Two out of two series subsystem, failure of any one can cause the failure of the entire system.

$$\frac{d}{dt}P_0(t) = -2K_2P_0 + \xi_2P_1 \quad (12)$$

$$\frac{d}{dt}P_1(t) = 2K_2P_0 - \xi_2P_1 \quad (13)$$

Under steady state, equation (8) and (9) reduces to

$$-2K_2P_0 + \xi_2P_1 = 2K_2P_0 - \xi_2P_1 \quad (14)$$

and

$$P_1 = \frac{2K_2}{\xi_2}P_0 \quad (15)$$

Using normalization condition

$$P_0 + P_1 = 1 \quad (16)$$

Substituting (10) into (11) we have

$$P_0 + \frac{2K_2}{\xi_2}P_0 = 1 \quad (17)$$

$$P_0 = \frac{\xi_2}{\xi_2 + 2K_2} \quad (19)$$

Availability = $A_{s2} = \left(\frac{0.09}{0.11}\right) = 0.81818$

Table 4 contains important device output metrics that have been extracted.
Dependability of subsystem 2

$$D_{min} = 1 - (\frac{1}{d-1})(e^{-\frac{lnd}{d-1}} - e^{-\frac{d\ln d}{d-1}}) \quad (20)$$

$$d = \frac{\xi}{K} = \frac{MTBF}{MTTR} \quad (21)$$

$d_2 = \frac{\xi_2}{K_2} = \frac{0.09}{0.01} = 9.00$

$D_{\min\,(s2)} = 1 - (\frac{1}{9-1})(e^{-0.27465} - e^{-2.47188})$

$D_{\min\,(s2)} = 0.91557$

The reliability of subsystem 2

$R_{s2}(t) = e^{-0.01t}$

Maintainability of subsystem 2

$M_{s1}(t) = 1 - e^{-0.09t}$

Other performance measures of system effectiveness of subsystem 1 are as follows

MTBF = 100.00

MTTR = 11.111

Dependability ratio = 9.00

RAMD indices for subsystem 3 (activated carbon filter)

Activated carbon filter: Y. K. Siong et al. [24] is used to purify water without leaving any harmful chemicals. Prototype is being made by using activated carbon and ultraviolet radiation system for water treatment. Surface area and porosity analysis. Scanning electron microscopy (SEM) is used to obtain the magnified image of GAC-A and GAC-B for comparison between the surface morphology. Two out of three parallel subsystem of the activated carbon filter were considered, failure of any two can cause the failure of the entire system.

$$\frac{d}{dt}P_0(t) = -2\mathrm{K}_3 P_0 + \boldsymbol{\xi_3} P_1 \quad (22)$$

$$\frac{d}{dt}P_1(t) = -(\mathrm{K}_3 + \boldsymbol{\xi_3})\, P_1 + 2\mathrm{K}_3 P_0 + \boldsymbol{\xi_3} P_2 \quad (23)$$

$$\frac{d}{dt}P_2(t) = -\boldsymbol{\xi_3} P_2 + \mathrm{K}_3 P_1 \quad (24)$$

Under steady state, equation (13) - (15) reduces to

$$P_1 = \frac{2\mathrm{K}_3}{\xi_3} P_0 \quad (25)$$

Substituting (16) into (15)

$$P_2 = \frac{2\mathrm{K}_3^2}{\xi_3^2} P_0 \quad (26)$$

Using normalization condition

$$P_0 + P_1 + P_2 = 1 \quad (27)$$

Substituting (16) and (17) into (18) we have

$$P_0 + \frac{2\mathrm{K}_3}{\xi_3} P_0 + \frac{2\mathrm{K}_3^2}{\xi_3^2} P_0 = 1 \quad (28)$$

$$\mathrm{P}_0 = \frac{\xi_3^2}{\xi_3^2 + 2\mathrm{K}_3^2 + 2\,\xi_3 \mathrm{K}_3} \quad (29)$$

Availability = $A_{s3} = \left(\frac{0.0121}{0.01585}\right) = 0.76341$

Table 4 contains important device output metrics that have been extracted.

Dependability of subsystem 3

$$D_{min} = 1 - \left(\frac{1}{d-1}\right)\left(e^{-\frac{lnd}{d-1}} - e^{-\frac{d\,ln\,d}{d-1}}\right) \quad (30)$$

$$d = \frac{\xi}{\mathrm{K}} = \frac{MTBF}{MTTR} \quad (31)$$

$d_3 = \frac{\xi_3}{\mathrm{K}_3} = \frac{0.11}{0.015} = 7.33$

$D_{\min\,(s3)} = 1 - \left(\frac{1}{6.33}\right)\left(e^{-0.31469} - e^{-2.30666}\right)$

$D_{\min\,(s3)} = 0.90041$

The reliability of subsystem 3

$R_{s3}(t) = e^{-0.015t}$

Maintainability of subsystem 1

$M_{s1}(t) = 1 - e^{-0.011t}$

Other performance measures of system effectiveness of subsystem 1 are as follows

MTBF = 66.667

MTTR = 9.091

Dependability ratio = 7.3333

RAMD indices for subsystem 4 (precision filter)

$$\frac{d}{dt}P_0(t) = -2\mathrm{K}_4 P_0 + \boldsymbol{\xi_4} P_1 \quad (32)$$

$$\frac{d}{dt}P_1(t) = 2\mathrm{K}_4 P_0 - \boldsymbol{\xi_4} P_1 \quad (33)$$

Under steady state, equation (20) and (21) reduces to

$$-2\mathrm{K}_4 P_0 + \boldsymbol{\xi_4} P_1 = 2\mathrm{K}_4 P_0 - \boldsymbol{\xi_4} P_1 \quad (34)$$

and

$$P_1 = \frac{2\mathrm{K}_4}{\xi_4} P_0 \quad (35)$$

Using normalization condition

$$P_0 + P_1 = 1 \quad (36)$$

Substituting (22) into (23) we have

$$P_0 + \frac{2\mathrm{K}_4}{\xi_4} P_0 = 1 \quad (37)$$

$$\mathrm{P}_0 = \frac{\xi_4}{\xi_4 + 2\mathrm{K}_4} \quad (38)$$

Availability = $A_{s4} = \left(\frac{0.13}{0.17}\right) = 0.76471$

Table 4 contains important device output metrics that have been extracted.

Dependability of subsystem 4

$$D_{min} = 1 - \left(\frac{1}{d-1}\right)\left(e^{-\frac{\ln d}{d-1}} - e^{-\frac{d \ln d}{d-1}}\right) \quad (39)$$

$$d = \frac{\xi}{\mathrm{K}} = \frac{MTBF}{MTTR} \quad (40)$$

$d_4 = \frac{\xi_4}{\mathrm{K}_4} = \frac{0.13}{0.02} = 6.50$

$D_{\min\,(s4)} = 1 - \left(\frac{1}{5.5}\right)\left(e^{-0.34033} - e^{-2.21213}\right)$

$D_{\min\,(s4)} = 0.89053$

The reliability of subsystem 4

$R_{s4}(t) = e^{-0.020t}$

Maintainability of subsystem 4

$M_{s4}(t) = 1 - e^{-0.13t}$

Other performance measures of system effectiveness of subsystem 1 are as follows

MTBF = 50.00

MTTR = 7.6923

Dependability ratio = 6.500

RAMD indices for subsystem 5 (RO membrane)

Reverse Osmosis Membrane P. A. Taylor [25]. RO membranes are normally deployed as cross-flow filters, where the high velocity of the wastewater along the filter keeps the flow turbulent which helps control the thickness of the solids on the filter and reduces plugging of the filter. Three out of five parallel subsystem of the RO membrane were considered, failure of any three can cause the failure of the entire system.

$$\frac{d}{dt}P_0(t) = -2K_5P_0 + \xi_5P_1 \quad (41)$$

$$\frac{d}{dt}P_1(t) = -(2K_1 + \xi_1)P_1 + 3K_5P_0 + \xi_5P_2 \quad (42)$$

$$\frac{d}{dt}P_2(t) = -(K_5 + \xi_5)P_2 + 2K_5P_1 + \xi_5P_3 \quad (43)$$

$$\frac{d}{dt}P_3(t) = -\xi_5P_5 + K_5P_5 \quad (44)$$

Under steady state, equation (25) - (27) reduces to

$$P_1 = \frac{3K_5}{\xi_5}P_0 \quad (45)$$

Substituting (29) into (26)

$$P_2 = \frac{6K_5^2}{\xi_5}P_0 \quad (46)$$

Substituting (30) into (28) we have

$$P_3 = \frac{6K_5^2}{\xi_5^2}P_0 \quad (47)$$

Using normalization condition

$$P_0 + P_1 + P_2 + P_3 = 1 \quad (48)$$

Substituting (30) and (31) into (33) we have

$$P_0 + \frac{3K_5}{\xi_5}P_0 + \frac{6K_5^2}{\xi_5}P_0 + \frac{6K_5^2}{\xi_5^2}P_0 = 1 \quad (49)$$

$$\mathrm{P}_0 = \frac{\xi_5^2}{\xi_5^2 + 3K_5\xi_5 + 6\xi_5K_5^2 + 6K_5^2} \quad (50)$$

Availability = A_{s5} = $\left(\frac{0.0225}{0.0380625}\right)$ = 0.59113

Table 4 contains important device output metrics that have been extracted.
Dependability of subsystem 5

$$D_{min} = 1 - \left(\frac{1}{d-1}\right)\left(e^{-\frac{lnd}{d-1}} - e^{-\frac{d\ln d}{d-1}}\right) \quad (51)$$

$$d = \frac{\xi}{K} = \frac{MTBF}{MTTR} \quad (52)$$

$d_5 = \frac{\xi_5}{K_5} = \frac{0.15}{0.025} = 6.00$

$D_{\min(s5)} = 1 - \left(\frac{1}{5}\right)\left(e^{-0.35835} - e^{-2.15011}\right)$

$D_{\min(s5)} = 0.88353$

The reliability of subsystem 5

$R_{s5}(t) = e^{-0.025t}$

Maintainability of subsystem 5

$M_{s5}(t) = 1 - e^{-0.15t}$

Other performance measures of system effectiveness of subsystem 1 are as follows

MTBF = 40.00

MTTR = 6.6667

Dependability ratio = 6.00

RAMD indices for subsystem 6 (Water producing tank)

Water producing Tank: The water is now pure and is pumped into a tank, where it is kept pressured until the faucet is turned on. The tank has two bladders that pressurize the water, allowing it to enter and escape as needed. The tank is constantly under pressure, and water only fills it to around two-thirds of the water inflow pressure. A bladder filled with compressed air sits at the bottom of the tank, and a butyl water bladder, a thick substance comparable to the interior lining of a steel food can, is at the top. When you turn on the faucet, the air pressure sends the water out in a constant stream simultaneously, the intake valve opens to allow more water in, maintaining a constant level of pressure driving the water out. Two out of two series subsystem for the Water producing tank, failure of any one can cause the failure of the entire system.

$$\frac{d}{dt}P_0(t) = -2K_6P_0 + \xi_6P_1 \quad (53)$$

$$\frac{d}{dt}P_1(t) = 2K_6P_0 - \xi_6P_1 \quad (54)$$

Under steady state, equation (34) and (35) reduces to

$-2K_6P_0 + \xi_6P_1 = 2K_6P_0 - \xi_6P_1$

and

$$P_1 = \frac{2K_6}{\xi_6}P_0 \quad (55)$$

Using normalization condition

$$P_0 + P_1 = 1 \quad (56)$$

Substituting (36) into (37) we have

$$P_0 + \frac{2K_6}{\xi_6}P_0 = 1 \quad (57)$$

$$P_0 = \frac{\xi_6}{\xi_6 + 2K_6} \quad (58)$$

Availability = $A_{s6} = \left(\frac{0.17}{0.23}\right) = 0.73913$

Table 4 contains important device output metrics that have been extracted.

Dependability of subsystem 6

$$D_{min} = 1 - \left(\frac{1}{d-1}\right)\left(e^{-\frac{\ln d}{d-1}} - e^{-\frac{d\ln d}{d-1}}\right) \quad (59)$$

$$d = \frac{\xi}{K} = \frac{MTBF}{MTTR} \quad (60)$$

$d_6 = \frac{\xi_6}{K_6} = \frac{0.17}{0.03} = 5.67$

$D_{\min\,(s6)} = 1 - \left(\frac{1}{4.67}\right)\left(e^{-0.37156} - e^{-2.10675}\right)$

$D_{\min\,(s6)} = 0.87837$

The reliability of subsystem 6

$R_{s6}(t) = e^{-0.030t}$ Type equation here.

Maintainability of subsystem 6

$M_{s6}(t) = 1 - e^{-0.17t}$

Other performance measures of system effectiveness of subsystem 1 are as follows

MTBF = 33.333

MTTR = 5.8824

Dependability ratio = 5.6667

System description

The RO system is used to treatment of water. In the RO system, cells are arranged in series-parallel configuration. RO system consists of six subsystems as described below.

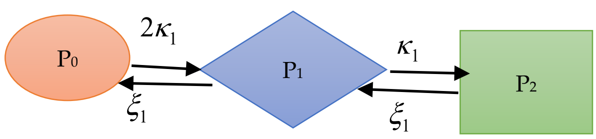


Figure 2: *Transition diagram of raw water tank*

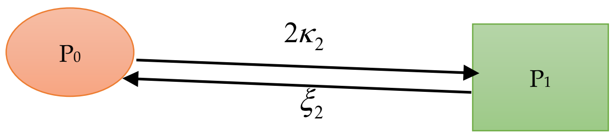


Figure 3: *Transition diagram of sand filter*

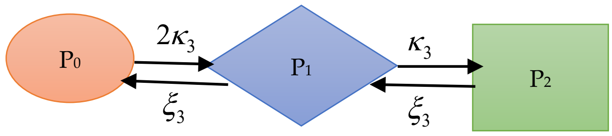


Figure 4: *Transition diagram of activated carbon filter*

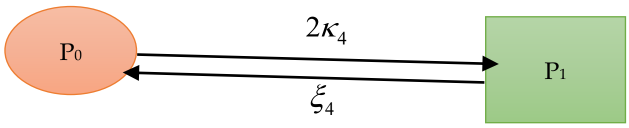


Figure 5: *Transition diagram of precision filter*

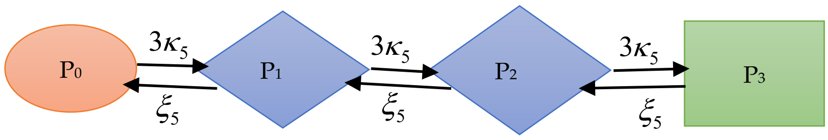


Figure 6: *Transition diagram of RO membrane*

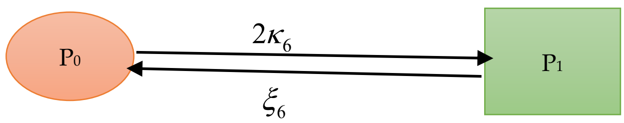


Figure 7: *Transition diagram of water producing tank*

Table1: *Failure and repair rates of component of the RO system*

Subsystem	Failure Rate (K)	Repair Rate (ξ)
S_1	K_1= 0.005	ξ_1 = 0.07
S_2	K_2= 0.010	ξ_2 = 0.09
S_3	K_3= 0.015	ξ_3 = 0.11
S_4	K_4= 0.020	ξ_4 = 0.13
S_5	K_5= 0.025	ξ_5=0.15
S_6	K_6= 0.030	ξ_6=0.17

III. Materials and methods

All of the measures discussed in this study are only valid in the steady-state era, when all failure and repair rates are exponentially distributed.

Reliability

The chance that a device will run without failure for a particular period of time is referred to as reliability under the operational conditions indicated.

$$R(t) = \int_t^{\infty} f(x)dx \tag{61}$$

MTBF

Mean Time between Failures (MTBF): The average period of good system functioning is referred to as the mean time between failures. When the failure rate is reasonably consistent over the operating period, the MTBF is the reciprocal of the constant failure rate or the ratio of the test time to the number of failures [26].

$$\text{MTBF} = \int_0^{\infty} R(t)dt = \int_0^{\infty} e^{-\theta t} = \frac{1}{\theta} \tag{62}$$

MTTR

Mean Time between repairs (MTTR): is the reciprocal of the system repair rate.

$$\text{MTTR} = \frac{1}{\xi} \tag{63}$$

Availability

Availability: Availability is a performance criterion for repairable systems that takes into consideration both the system's dependability and maintainability. It is defined as the likelihood that the system will function properly when it is needed [28].

$$\text{Availability} = \frac{Life\ time}{Total\ time} = \frac{Life\ time}{Life\ time + Repair\ time} = \frac{MTTF}{MTTF+MTTR} \tag{64}$$

Maintainability

Maintainability: [28] is a design, installation, and operation feature that is generally stated as the likelihood that a machine can be kept in, or returned to, a given operational condition within a specified time interval when maintenance is necessary.

$$M(t) = 1 - e^{(-\frac{-t}{MTTR})} \tag{65}$$

Dependability [27] dependability was stated as a design element It assesses performance by utilizing average failure and repair rates, as well as dependability and availability. The benefit of dependability is that it allows for the comparison of cost, reliability, and maintainability. The dependability ratio for random variables with exponential distribution is as follows:

$\boldsymbol{\xi} = Repair\ rate$, K = Failure rate

$d = \frac{\beta}{\lambda} = \frac{MTBF}{MTTR}$

The high value of dependability ratio represents the necessity of maintenance. C. Li, S. Besarati, and colleagues [10] mentioned that the dependability value increases if availability is above 0.9 and decrease if availability is less than 0.1. the minimum value of dependability is given by:

$$D_{min} = 1 - (\frac{1}{d-1})(e^{-\frac{lnd}{d-1}} - e^{-\frac{d\ln d}{d-1}}) \tag{66}$$

System Reliability

$$R_{sys}(t) = R_{s1}(t) \times R_{s2}(t) \times R_{s3}(t) \times R_{s4}(t) \times R_{s5}(t) \times R_{s6}(t)$$
$$= e^{-(K_1+K_2+K_3+K_4+K_5+K_6)t} \tag{67}$$

System Availability

Arranged in series, failure of one cause the complete failure of the system.

$$A_{sys} = A_{s1} \times A_{s2} \times A_{s3} \times A_{s4} \times A_{s5} \times A_{s6} \tag{68}$$

$$A_{sys} = (\frac{\xi_1}{\xi_1+2K_1^2+2K_1}) \times (\frac{\xi_2}{\xi_2+2K_2}) \times (\frac{\xi_3^2}{\xi_3^2+2K_3^2+2\,\xi_3K_3}) \times (\frac{\xi_4}{\xi_4+2K_4}) \times (\frac{\xi_5^2}{\xi_5^2+3K_5\xi_5+6\,\xi_5K_5^2+6K_5^2}) \times (\frac{\xi_6}{\xi_6+2K_6})$$

$$A_{sys} = \left(\frac{0.07}{0.08005}\right) \times \left(\frac{0.09}{0.11}\right) \times \left(\frac{0.0121}{0.01585}\right) \times \left(\frac{0.13}{0.17}\right) \times (\frac{0.0225}{0.0380625}) \times \left(\frac{0.17}{0.23}\right)$$

$A_{sys} = 0.87445 \times 0.81818 \times 0.76341 \times 0.76471 \times 0.59113 \times 0.73913$

$A_{sys} = 0.18249$

System Maintainability

$$M_{sys}(t) = M_{s1}(t) \times M_{s2}(t) M_{s3}(t) \times M_{s4}(t)) \times M_{s5}(t)\ ) \times M_{s6}(t) \tag{69}$$
$$= (1 - e^{-\xi_1(t)}) \times (1 - e^{-\xi_2(t)}) \times (1 - e^{-\xi_3(t)}) \times (1 - e^{-\xi_4(t)})\ ) \times (1 - e^{-\xi_5(t)})) \times (1 - e^{-\xi_6(t)})$$

$$1 - e^{-(\xi_1+\xi_2+\xi_3+\xi_4+\xi_5+\xi_6)t} \tag{70}$$
$$= (1 - e^{-\mathbf{0.07}(t)}) \times (1 - e^{-\mathbf{0.09}(t)}) \times (1 - e^{-\mathbf{0.11}(t)}) \times (1 - e^{-\mathbf{0.13}(t)})\ ) \times (1 - e^{-\mathbf{0.15}(t)})) \times (1 - e^{-\mathbf{0.17}(t)})$$
$$= 1 - e^{-\mathbf{0.72}(t)}$$

System dependability

$D_{\min\,(sys)} = D_{\min\,(s1)} \times D_{\min\,(s2)} \times D_{\min\,(s3)} \times D_{\min\,(s4)} \times D_{\min\,(s5)} \times D_{\min\,(s6)}$

$D_{min} = 1 - (\frac{1}{d-1})(e^{-\frac{ln d}{d-1}} - e^{-\frac{d\, ln\, d}{d-1}})$

$d = \frac{\xi}{K} = \frac{MTBF}{MTTR}$

$d_1 = \frac{\xi_1}{K_1} = \frac{0.07}{0.005} = 14.00$

$d_2 = \frac{\xi_2}{K_2} = \frac{0.09}{0.01} = 9.00$

$d_3 = \frac{\xi_3}{K_3} = \frac{0.11}{0.015} = 7.33$

$d_4 = \frac{\xi_4}{K_4} = \frac{0.13}{0.02} = 6.50$

$d_5 = \frac{\xi_5}{K_5} = \frac{0.15}{0.025} = 6.00$

$d_6 = \frac{\xi_6}{K_6} = \frac{0.17}{0.03} = 5.67$

$D_{\min\,(s1)} = 1 - (\frac{1}{14-1})(e^{-\frac{2.6391}{13}} - e^{\frac{36.9468}{13}})$

$D_{\min\,(s1)} = 1 - 0.05831$

$D_{\min\,(s1)} = 0.94169$

$D_{\min\,(s2)} = 1 - (\frac{1}{9-1})(e^{-0.27465} - e^{-2.47188})$

$D_{\min\,(s2)} = 0.91557$

$D_{\min\,(s3)} = 1 - (\frac{1}{6.33})(e^{-0.31469} - e^{-2.30666})$

$D_{\min\,(s3)} = 0.90041$

$D_{\min\,(s4)} = 1 - (\frac{1}{5.5})(e^{-0.34033} - e^{-2.21213})$

$D_{\min\,(s4)} = 0.89053$

$D_{\min(s5)} = 1 - \left(\frac{1}{5}\right)(e^{-0.35835} - e^{-2.15011})$

$D_{\min\,(s5)} = 0.88353$

$D_{\min\,(s6)} = 1 - (\frac{1}{4.67})(e^{-0.37156} - e^{-2.10675})$

$D_{\min\,(s6)} = 0.87837$

$D_{\min(sys)} = 0.94169 \times 0.91557 \times 0.90041 \times 0.89053 \times 0.88353 \times 0.87837$

$D_{\min(sys)} = 0.53652$

Table 2: *Variation of reliability of subsystems with time*

Time (in days)	$R_{s1}(t)$	$R_{s2}(t)$	$R_{s3}(t)$	$R_{s4}(t)$	$R_{s5}(t)$	$R_{s6}(t)$	$R_{sys}(t)$
0	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
30	0.86071	0.74082	0.63763	0.54881	0.47237	0.40657	0.04285
60	0.74082	0.54881	0.40657	0.30119	0.22313	0.16530	0.00184
90	0.63763	0.40657	0.25924	0.16530	0.10540	0.06721	7.0×10^{-5}
120	0.54881	0.30119	0.16530	0.09072	0.04979	0.02732	3.37×10^{-6}
150	0.47237	0.22313	0.10540	0.04979	0.02352	0.01111	1.44×10^{-7}
180	0.40657	0.16530	0.06721	0.02732	0.01111	0.00452	6.19×10^{-9}
210	0.34994	0.12246	0.04285	0.01500	0.00525	0.00184	2.66×10^{-10}
240	0.25924	0.09072	0.02732	0.00823	0.00248	0.00075	9.83×10^{-12}
270	0.22313	0.06721	0.01742	0.00452	0.00117	0.00030	4.11×10^{-13}
300	0.19205	0.04979	0.01111	0.00248	0.00055	0.00012	1.74×10^{-14}
330	0.16530	0.03688	0.00708	0.00136	0.00026	0.00005	7.63×10^{-16}
360	0.14227	0.02732	0.00452	0.00075	0.00012	0.00002	3.16×10^{-17}

Table 3: *Variation of Maintainability of subsystems with time*

Time (in days)	$M_{s1}(t)$	$M_{s2}(t)$	$M_{s3}(t)$	$M_{s4}(t)$	$M_{s5}(t)$	$M_{s6}(t)$	$M_{sys}(t)$
0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
30	0.87754	0.93279	0.96312	0.97976	0.98889	0.99390	0.75917
60	0.98500	0.99548	0.99864	0.99959	0.99988	0.99996	0.97866
90	0.99816	0.99970	0.99995	0.99999	0.99999	1.00000	0.99779
120	0.99978	0.99998	0.99999	1.00000	1.00000	1.00000	0.99975
150	0.99997	0.99999	1.00000	1.00000	1.00000	1.00000	0.99996
180	0.99999	1.00000	1.00000	1.00000	1.00000	1.00000	0.99999
210	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
240	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
270	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
300	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
330	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
360	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000

Table 4: *RAMD indices for the R.O system*

RAMD indices of Subsystems	Subsystem S_1	Subsystem S_2	Subsystem S_3	Subsystem S_4	Subsystem S_5	Subsystem S_6	System
Reliability	$e^{-0.005t}$	$e^{-0.01t}$	$e^{-0.015t}$	$e^{-0.020t}$	$e^{-0.025t}$	$e^{-0.030t}$	$e^{-0.105t}$
Maintainability	$1-e^{-0.07t}$	$1-e^{-0.09t}$	$1-e^{-0.11t}$	$1-e^{-0.13t}$	$1-e^{-0.15t}$	$1-e^{-0.10t}$	$1-e^{-0.72t}$
Availability	0.87445	0.81818	0.76341	0.76471	0.59113	0.73913	0.18249
MTBF	200.000	100.000	66.667	50.000	40.000	33.333	490.0003
MTTR	14.286	11.111	9.091	7.6923	6.6667	5.8824	54.7294
Dependability	0.94169	0.91557	0.90041	0.89053	0.88353	0.87837	0.53652
Dependability ratio	14.000	9.00000	7.33330	6.50000	6.00000	5.66667	

Table 5: *Variation of reliability of system due to variation in failure rate of raw water tank (subsystem 1)*

	R.O System		raw water tank (Subsystem 1)	
Time (in days)	$K_1 = 0.0001$	$K_1 = 0.0002$	$K_1 = 0.0001$	$K_1 = 0.0002$
0	1.00000	1.00000	1.00000	1.00000
10	0.36751	0.36714	0.99900	0.99800
20	0.13506	0.13480	0.99800	0.99601
30	0.04964	0.04949	0.99700	0.99402
40	0.01824	0.01817	0.99601	0.99203
50	0.00670	0.00667	0.99501	0.98020
60	0.00246	0.00245	0.99402	0.98807
70	0.00091	0.00090	0.99302	0.98610
80	0.00033	0.00029	0.99203	0.98413
90	0.00012	0.00012	0.99104	0.98216
100	0.00004	0.00004	0.99005	0.98020

Table 6: *Variation of reliability of system due to variation in failure rate of sand filter (subsystem 2)*

	R.O System		sand filter (subsystem 2)	
Time (in days)	$K_2 = 0.0003$	$K_2 = 0.0004$	$K_2 = 0.0003$	$K_2 = 0.0004$
0	1.00000	1.00000	1.00000	1.00000
10	0.38558	0.38520	0.99700	0.99601
20	0.14867	0.14838	0.99402	0.99203
30	0.05733	0.05715	0.99104	0.98807
40	0.02210	0.02202	0.98807	0.98413
50	0.00852	0.00848	0.98511	0.98020
60	0.00329	0.00327	0.98216	0.97629
70	0.00127	0.00126	0.97922	0.97239
80	0.00049	0.00048	0.97629	0.96851
90	0.00019	0.00019	0.97336	0.96464
100	0.00007	0.00002	0.97045	0.96079

Table 7: *Variation of reliability of system due to variation in failure rate of activated carbon filter (subsystem 3)*

	R.O System		Act. carbon filter (Subsystem 3)	
Time (in days)	$K_3 = 0.0005$	$K_3 = 0.0006$	$K_3 = 0.0005$	$K_3 = 0.0006$
0	1.00000	1.00000	1.00000	1.00000
10	0.40454	0.40414	0.99501	0.99402
20	0.16365	0.16333	0.99005	0.98807
30	0.06620	0.06601	0.98511	0.98216
40	0.02678	0.02668	0.98020	0.97629
50	0.01083	0.01078	0.97531	0.97045
60	0.00438	0.00436	0.97045	0.96464
70	0.00177	0.00176	0.96561	0.95887
80	0.00072	0.00071	0.96079	0.95313
90	0.00029	0.00029	0.95600	0.94743
100	0.00012	0.00012	0.95123	0.94176

Table 8: *Variation of reliability of system due to variation in failure rate of precision filter (subsystem 4)*

	R.O System		precision filter (Subsystem 4)	
Time (in days)	$K_4 = 0.0007$	$K_4 = 0.0008$	$K_4 = 0.0007$	$K_4 = 0.0008$
0	1.00000	1.00000	1.00000	1.00000
10	0.42443	0.42401	0.99302	0.99203
20	0.18014	0.17978	0.98610	0.98413
30	0.07646	0.07623	0.97922	0.97629
40	0.03245	0.03232	0.97239	0.96851
50	0.01377	0.01370	0.96561	0.96079
60	0.00585	0.00581	0.95887	0.95313
70	0.00248	0.00246	0.95218	0.94554
80	0.00105	0.00104	0.94554	0.93800
90	0.00045	0.00044	0.93894	0.93053
100	0.00019	0.00019	0.93239	0.92312

Table 9: *Variation of reliability of system due to variation in failure rate of R.O membrane (subsystem 5)*

	R.O System		R.O membrane (Subsystem 5)	
Time (in days)	$K_5 = 0.0009$	$K_5 = 0.0010$	$K_5 = 0.0009$	$K_5 = 0.0010$
0	1.00000	1.00000	1.00000	1.00000
10	0.44530	0.44486	0.99104	0.99005
20	0.19829	0.19790	0.98216	0.98020
30	0.08830	0.08804	0.97336	0.97045
40	0.03932	0.03916	0.96464	0.96079
50	0.01751	0.01742	0.95600	0.95123
60	0.00780	0.00775	0.94743	0.94176
70	0.00347	0.00345	0.93894	0.93239
80	0.00155	0.00153	0.93053	0.92312
90	0.00069	0.00068	0.92219	0.91393
100	0.00031	0.00030	0.91393	0.90484

Table 10: *Variation of reliability of system due to variation in failure rate of water producing tank (subsystem 6)*

	R.O System		producing tank (Subsystem 6)	
Time (in days)	$K_6 = 0.0011$	$K_6 = 0.0012$	$K_6 = 0.0011$	$K_6 = 0.0012$
0	1.00000	1.00000	1.00000	1.00000
10	0.46720	0.46673	0.98906	0.98807
20	0.21827	0.21784	0.97824	0.97629
30	0.10198	0.10167	0.96754	0.96464
40	0.04764	0.04745	0.95695	0.95313
50	0.02226	0.02215	0.94649	0.94176
60	0.01040	0.01034	0.93613	0.93053
70	0.00486	0.00482	0.92589	0.91943
80	0.00227	0.00225	0.91576	0.90846
90	0.00106	0.00105	0.90574	0.89763
100	0.00050	0.00049	0.89583	0.88692

IV. Discussion

The reliability and maintenance characteristics of all subsystems are shown in Tables 2 and 3. All of the extra RAMD metrics are listed in Table 4. According to the numerical analysis in table 2, the system's reliability after 60 days of operation is just 0.00184. It happened because of the least reliable subsystems, the R.O membrane and water producing tank (subsystem 5 and 6), whose corresponding reliability are 0.22313 and 0.16530 respectively. In this case, it is recommended that weak performance be given more attention and that suitable maintenance methods be established to enhance their reliability. The maintainability of the system after 60 days is just 0.97866. While the correspondent value for the RO membrane i.e. subsystem 5 is 0.99988. Attention is highly needed to the subsystem by providing more redundant and possible replacement of the affected subsystem i.e. subsystems 5 and 6 although the maintainability sound good. Tables 5, 6, 7, 8, 9, and 10 illustrated the time-dependent reliability behavior of several subsystems as well as the variability in their failure rates. Precision filters and R.O Membrane systems are the most critical, highly sensitive components that necessitate special attention in order to improve system reliability. According to the preceding discussion, regular maintenance plans that properly monitor the failure rates of the Precision filter and R.O Membrane system will surely enhance the efficacy and working time of the reverse osmosis system of water treatment.

V. Conclusion

Through desalination, RO is a significant technique for generating drinkable water from saltwater. The failure behavior of a desalination system's components determines its performance. Because the RO system was designed to be a power-saving system, the dependability of its subsystems must be maintained at a high level by correct design and material selection of these subsystems for continuous plant operation Thus, in this study, the system's availability and reliability were examined, as well as other characteristics such as MTTF, MTTR, dependability analysis, and maintainability.

The design of an integrated RO system is recommended because it is high performing, consumes little power, and is cost effective.

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