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Availability and reliability analysis of integrated reverse osmosis – forward osmosis desalination network

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ABSTRACT

The hybrid desalination of reverse osmosis (RO) with forward osmosis (FO) is an innovative technology for freshwater production worldwide, which provides many advantages such as RO fouling and scaling, recovery of the energy of RO brine, minimizing the power consumption and minimizing the use of chemicals required for conventional pretreatment steps. For this reason, breakdowns, blockage of the membrane, pressure losses and preventive maintenance have to be minimized in duration and frequency to ensure the maximum availability and indeed improving the availability or reliability of the system leads objectively to the reduction of operating costs. In this study, hybrid fault tree analysis method based fuzzy set theory was considered to evaluate the availability and reliability of the integrated RO–FO desalination system. For assessing availability, the system was divided into four subsystems such as seawater intake pump, pressurization stage, FO stage and RO stage. The data were collected from reliability data bank and probabilities estimated by considering the fuzzy set theory, wherever detailed data were not available. The overall unavailability of the hybrid system was 0.0156.

Keywords: Hybrid desalination system; Availability; Reliability; Fault tree analysis; Failure probabilities

1. Introduction

The development of human life depends on the availability of freshwater resources. Some regions have limited resources of freshwater while the others have abundant resources. According to the study, more than one billion of people do not have access to freshwater [1]. The global freshwater demand increases so that it is predicted that water scarcity is becoming new rising challenge [2].

Desalination is recognized as a necessary alternative to overcome the water shortage dilemma [3]. Various desalination technologies were employed and are classified into two categories: distillation and membrane technologies. Distillation converts saltwater into steam and then condenses into liquid. Distillation process consumes thermal and electrical energy. Multi-stage flash, multi-effect distillation and vapor compression are the dominant distillation technologies. Membrane processes such as reverse osmosis (RO), electrodialysis and an emerging technology forward osmosis (FO) are used for different desalination purposes. The desalination technologies using membrane require energy as mechanical or electrical. However, RO has the largest installed capacity among them [4].

In the last few years, a growing interest in the application of FO phenomenon in seawater desalination was observed. It is being investigated through laboratory and pilot scale and has proved several advantages [5]. In FO, the flow of water across the semi-permeable membrane occurs due to the osmotic pressure gradient between the two sides of the membrane. This process is established with no energy cost for transmembrane flow except that required to circulate solutions in the system. The osmotic driving forces in FO can

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be significantly greater than hydraulic driving forces in RO, leading to higher water flux rates and recoveries [6].

The FO desalination process involves two steps. First, the freshwater is extracted from the raw water source using a draw solution while the second step deals with separation of the osmotic agent from the freshwater. Many options were suggested including integration of FO with current RO desalination process. The FO process was suggested as a membrane pretreatment step for seawater prior to RO desalination and has been used to desalinate feed streams ranging from brackish water to saline [7]. Among several hybrid FO systems, RO–FO hybrid desalination system, which first proposed by Cath et al. [5] and later studied by Kolluri et al. [8] to increase the product water quality and to reduce the power consumption of seawater desalination. Cost reductions are attributed to lower energy requirement for pretreatment and RO process, fewer pretreatment processes, lower maintenance and chemical costs and decrease in RO membrane costs.

One of the important performance measures of any continuously operating desalination system, apart from its product water quality, power consumption and recovery ratio, is the overall availability. Integrated RO–FO system was designed for continuous operation; the availability of the system was considered more appropriate than reliability and used as an indicator of reliability. Improving the availability of the system results in a frequent reduction in total production cost if availability and reliability are maintained at high level.

During the last few decades, researchers around the world have continued to make the improvement to the desalination processes as the quality of membranes, energy recovery and combining various desalination processes to improve the performance. On the other hand, only a few studies are interested in improving the reliability and the availability of desalination systems. Hajeeh and Chaudhuri [9] tried to assess the availability of one RO plant operating in Kuwait using fault tree analysis (FTA) method and showed that the availability of the whole plant strongly depends on the plant design and selection of subsystem's material. Kutbi et al. [10] applied the same approach (FTA) for reliability analysis of RO plants operating in Jeddah, Saudi Arabia and showed that the seawater intake system needs some improvements and a proper preventive maintenance should be applied. Bourouni [11] compared the two methods: FTA and reliability block diagram (RBD) for availability assessment of one of the RO plant operating in Kuwait and showed that the FTA is too difficult to apply for complex systems.

Having reviewed the relevant literature, significant effort has been devoted to performing the availability and reliability study of RO plant. The reliability and availability of the integrated RO–FO system should observe to improve the system design and its operation. However, it is often difficult to estimate precise failure probability of the components due to vague characteristics of the events. Fuzzy methods might be the only way when data are insufficient and vague. The fuzzy set theory was introduced by Zadeh [12] to deal with the problem in which the phenomena are imprecise and vague. The fuzzy set theory provides a useful tool for directly working with the linguistic expression in reliability analyses. Hence, the fuzzy set concept was used to assess the failure rate of vague events to estimate the probabilities of human unpredictability errors.

The main aim of the paper was to estimate the availability and the reliability of the integrated RO–FO network desalination system and contribute to assessing the performance of the system, by utilizing FTA and fuzzy sets. The goal was realized by achieving the following two objectives:

- To identify the causes and sequences of failures in the integrated RO–FO network.
- To assess the failure rate of the integrated RO–FO network by identifying the components and events causing downtime and unwanted effects.

2. Availability and reliability assessment of desalination network

The objective of the availability and the reliability of any continuously operating system is to maintain the desired level of production on a continuous basis without failures and to restore the system as each time it suffers from failure [13]. Thus, management can achieve the minimum total cost of production if availability and reliability are maintained at a high level.

The reliability and availability of a system are systematic approach used to identify and assess the frequency and causes of failures. It reduces and controls the effects of failure to ensure satisfactory performance of the system [14]. Human errors and component failures do not only affect the performance of the system but can also cause accidents. The frequencies of such events are assessed during system design and its operation. To enhance the performance and maximize the profit of system, reliability analysis has to be done at the design stage.

2.1. Availability and reliability

Reliability is defined as the ability of a device to perform a required function under specified conditions during a given period [15]. If the time-to-failure distribution indicates the reliability ($R(t)$) of the integrated system and especially exponential distribution with constant failure rate (ζ), the reliability function of the steady state system is given by Eq. (1):

$$R(t) = e^{-\zeta t} \tag{1}$$

Maintainability is an important factor while designing any continuously operating system. As the total downtime is composed of the time for inspection and detection of faults, then the time of repair faults and administrative time can be minimized to reduce the total downtime. The maintainability in terms of downtime is given in Eq. (2) as follows:

$$M(t) = 1 - e^{-\mu t} \tag{2}$$

Here, $M(t)$ represents the maintainability function and μ represents the mean downtime in negative exponential function. Since both reliability and maintainability are important factors for continuously operating systems, these two factors can be combined into one measure, availability.

Availability is defined as the fraction of the time that a component and system are able to perform its required function [16]. The availability can be classified into two distinct senses: interval availability such as the probability that a system works on demand and inherent availability such as the probability that the system is working at the specific time. It can be used for continuously operating the system and determined by Eq. (3) as follows:

$$A(t) = \frac{O}{O+D} \tag{3}$$

Here, $A(t)$ is the availability of the system, O and D indicate the uptime and downtime, respectively. Availability represents the probability that a system is in use at a given time t interval and can be calculated using Eq. (4):

$$A = \frac{\text{MTTF}}{\text{MTTF}+\text{MTTR}} = \frac{\mu}{\mu+\zeta} \tag{4}$$

$$\overline{A} = \frac{\text{MTTR}}{\text{MTTR}+\text{MTTF}} = \frac{\zeta}{\zeta+\mu} \tag{5}$$

where $\overline{A}$ in Eq. (5) represents the unavailability of the system. MTTF is the mean time to failure and MTTR is the mean time to repair and equivalent to (1/μ) and (1/ζ), respectively. In above equations availability A is determined from failure rate (ζ) and repairing rate (μ) assumed to be constant [17] (exponential distribution).

2.2. Availability modeling methods of industrial system

For analyzing the reliability of any designed and operated system, many methods have been developed such as FTA, failure mode effects and criticality analysis (FMECA), RBD, reliability graph and Poisson's process. Fig. 1 shows the different methods used in reliability and availability assessment [18]. Each method has its own pros and cons. FMECA is qualitative analysis and reviewed many components, assemblies and subsystems to identify the failure modes, critical failures and their causes and effects. Monte Carlo simulation draws a realization of each random variable and then estimates which units are down and for how long. The system availability over the time can be determined based on these calculations. Among all analytical techniques, FTA is the most important method used for reliability and availability assessment of different kinds of systems.

FTA is a well-known probabilistic approach in the domain of RAMS (reliability, availability, maintainability and safety). FTA is a bottom-to-top (deductive) methodology for estimating the potential causes of accidents and failure probabilities. FTA is centered about determining the causes of undesirable events, while referred as the top event. Fault trees (FTs) are drawn at the top of the events. It the proceeds downward, dissecting the system in increasing details to determine the root causes or combinations of causes of the top event. Top events are usually considered as the major failure consequences, engendering serious safety hazards and the potential for significant economic loss.

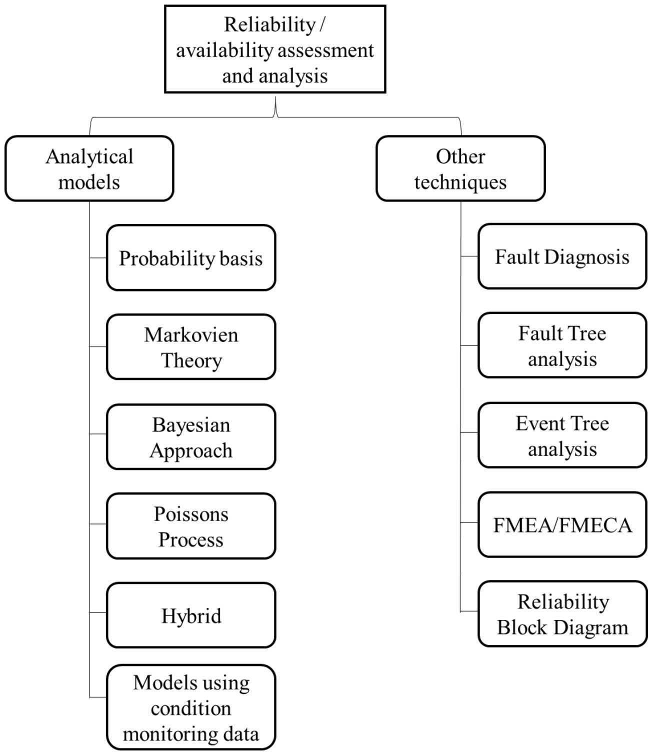

Fig. 1. Different methods for reliability and availability assessment [17].

Both quantitative and qualitative information about the system are obtained from FTA. The construction of FT provides a better understanding of the potential sources of failures, which will lead to rethink the design and the operation perspective to eliminate the potential hazards. FT can analyze the system to identify the combinations of component failures, operational errors, or other faults that initiate the top event. Finally, it may be used to calculate the demand failure probability, unreliability and unavailability of any system.

FT is a logical diagram that depicts the relationship between the events giving rise to the failure. "AND gates" are used to connect the groups of events and conditions, if all of them are required to be present simultaneously to cause the hazardous event to occur, which is shown in Fig. 2(a), while "OR gates" represents the existence of the alternative ways in which a failure can occur, is shown in Fig. 2(b).

Consider the "AND" and "OR" FT as given in Fig. 2 where the simultaneous existence of the events E_1, E_2 … E_n results in the top events and the top event exist at time t if and only if at least one of the n basic event occurs at time t, respectively. Thus, the system unavailability is given by Eqs. (6) and (7), respectively.

$$\overline{A}_s(t) = \prod_{i-1}^{i-n} \overline{A}_i = \Pr(E_1 \cap E_2 ... \cap E_n) = \Pr(E_1)\Pr(E_2)...\Pr(E_n) \tag{6}$$

$$\overline{A}_s(t) = 1 - \prod_{i-1}^{i-n}(1-\overline{A}_i) = \Pr(E_1 \cup E_2 ... \cup E_n) = 1 - \prod_{i-1}^{i-n}(1-\Pr(E_i) \tag{7}$$

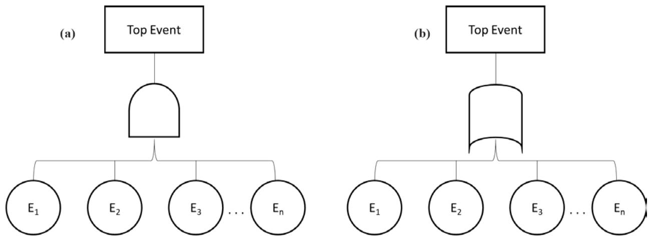

Fig. 2. Schematic representation of fault tree gates. (a) AND gate and (b) OR gate.

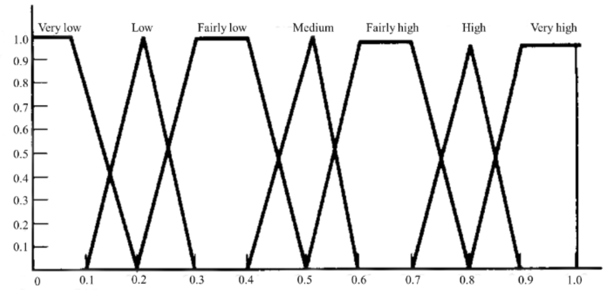

Fig. 3. The fuzzy number represents linguistic values [19].

3. Methodology of RO–FO desalination network

Probabilities of the basic events must be known in advance in order to evaluate the failure probability of the top event. The fuzzy set theory was used to get the probabilities of the basic events in this study. The human error rate, the expert's subjective assessments with linguistic variables were represented in fuzzy possibility scores (FPSs).

The evaluation data were expressed in linguistic terms such as very low, low, fairly low, medium, fairly high, high and very high. Fig. 3 represented the fuzzy number of these linguistic values [19]. The fuzzy number is used to handle imprecise information. There are many forms of fuzzy numbers to represent the linguistic values. The triangular and trapezoidal fuzzy numbers were used here to denote failure possibilities. Transformation function was used to convert the FPS into fuzzy failure rate (FFR) given by Eqs. (8) and (9).

$$\text{FFR} = \frac{\text{frequency of an error}}{\text{total chance that an event having error}} \tag{8}$$

Swain and Guttmann [20] suggested that the error rate of a routine human operation is 10^{-2} to 10^{-3} and the lower bound of the error rate is 5×10^{-5}.

$$\text{FFR} = \begin{cases} 1/10^{k}, & \text{FPS} \neq 0, \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

Here, $k = [(1 - \text{FPS})/\text{FPS}]^{1/3} \times a$, where $a = 2.301$. The constant a is appropriate estimation of failure rate of desalination system. It can be realized that the range of failure rate obtained by the fuzzy probability score corresponds with the range of human error data suggestion by Swain and Guttmann [20]. The value of k is taken from Lin and Wang [19]. Lastly, unavailability of the integrated system was estimated by combining the hardware failure rate and the FPS of human error from the top event of FTA.

3.1. Integrated RO–FO system description

The schematic process flow diagram of the investigated system is shown in Fig. 4 proposed by Kolluri et al. [8]. The integrated system produced freshwater in minimum power consumption based on FO and RO principles. The main system comprises two main stages: RO and

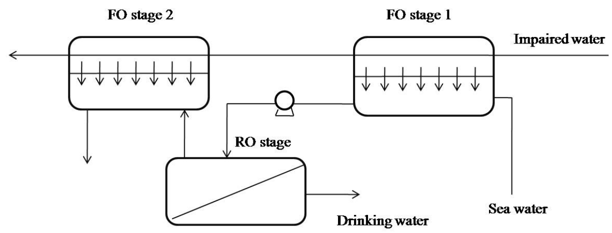

Fig. 4. Schematic superstructure representation of RO–FO integrated desalination system [8].

FO stage which are coupled mechanically. In the RO–FO process, draw solution and seawater are pumped into the FO membrane in an opposite direction of flow mode. Freshwater will cross the FO membrane from the feed to the draw solution side of the membrane in the direction of the osmotic pressure gradient. After leaving the FO membrane, now the diluted draw solution is input to RO subsystem for freshwater production and osmotic agent recycling and reuse. RO stage rejects salts and dissolved contaminants that may have crossed the membrane from the impaired water source. A second-stage FO process can be implemented to dilute seawater before discharge and to further concentrate and reduce the volume of the impaired water stream. Most important, because brine of RO subsystem is used as high salinity stream and seawater is used as low salinity stream in FO subsystem, the energy required for subsequent RO desalination of the diluted saline water is reduced.

3.2. Hybrid FTA algorithm

A stepwise description of the hybrid FTA algorithm of integrated RO–FO desalination system.

- Select the top event and construct FT logic diagram.
- Divide the elements of FT logic diagram into objective probability analysis and subjective linguistic evaluation of human performance and vague events.
- Select hardware failure-rate estimation from data bank.
- Conduct linguistic expressions for human performance and vague events and transform into fuzzy number.
- Convert fuzzy numbers into FPSs and transform into FFR.
- Integrate both failure-rate to estimate the failure-rate of top event and unavailability or reliability of the system.

4. Results and discussion

The system availability was computed based on Oreda report 2002 [21], recorded data and fuzzy set. A FT diagram was drawn for the integrated system using AND and OR gates as shown in Fig. 5. The output of these gates in terms of unavailability was computed. The most important parameters considered for estimating the unavailability of the RO–FO system were semi-permeable membranes, filters, high-pressure pumps (HPPs), pipeline leakages, instruments and controls. Unavailability of the system due to power supply disruption was not considered in the overall estimation of unavailability. Since it is independent of the RO and FO technology. The unavailability of the RO–FO system was estimated using "AND" and "OR" gates as given in Eqs. (6) and (7).

4.1. Hybrid FTA failure rate calculation

Step 1: Divide the elements of fault-tree logic diagram into objective probability analysis and fuzzy linguistic evaluation for human performance and vague events. Events such as careless operation, noise, external leakages, inadequate microbial control, monitoring and equipment design were categorized as fuzzy subjective evaluation events. Other events of system unavailability were categorized under objective probability analysis. The fuzzy linguistic evaluation events were represented in shaded blocks in Fig 5.

Step 2: Failure rate estimation was obtained by referring the Oreda report 2002 [21]. The failure rate of corresponding component faults shown in Table 1.

Step 3: For human performance and vague events, conducted the linguistic assessment and assigned the scale rating (such as very low, low, fairly low, medium, fairly high, high and very high) to each fault based on expert opinion.

Step 4: After obtaining the fuzzy number, convert fuzzy numbers into FPSs. This was done by using Eqs. (10) through (14).

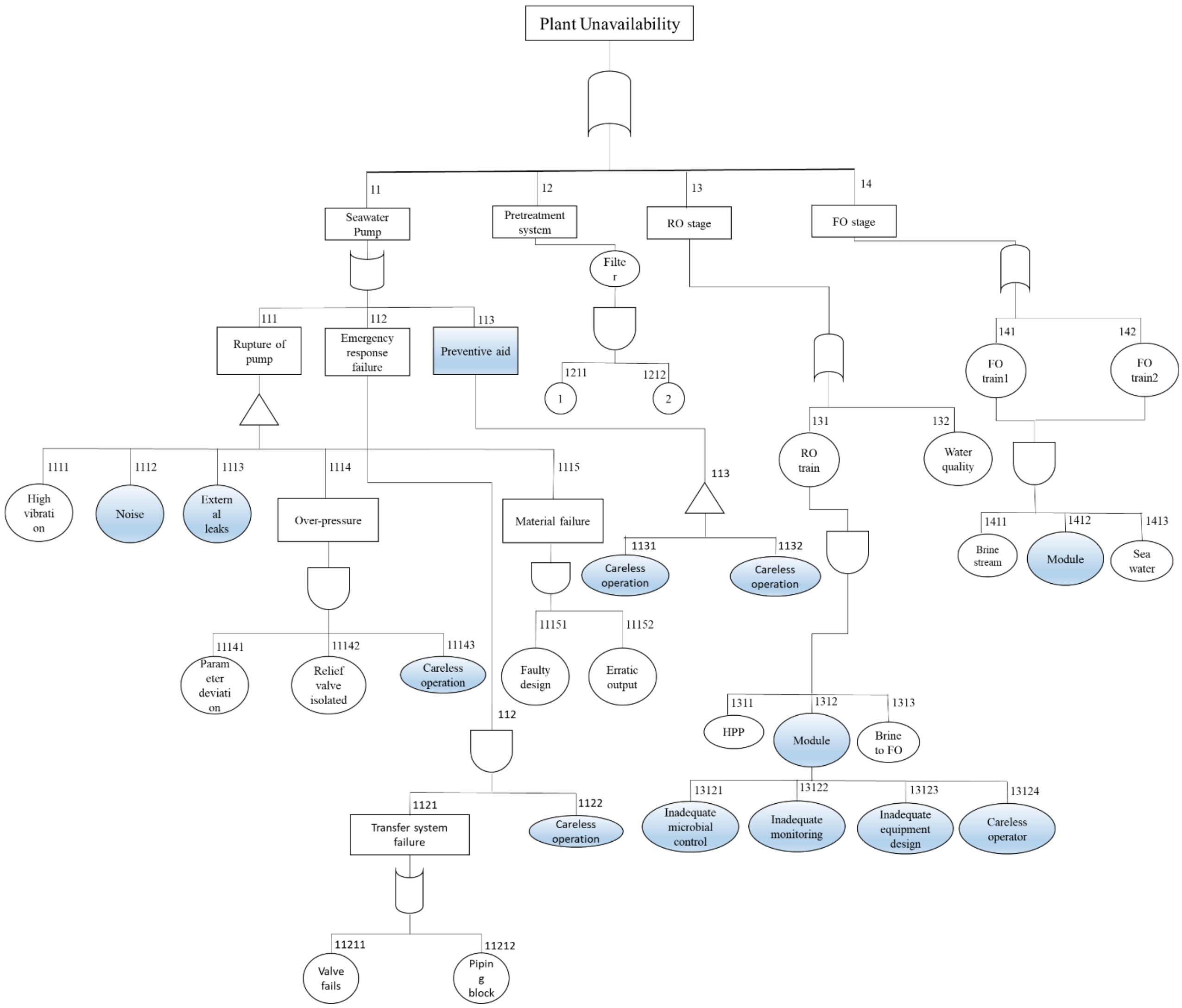

Fig. 5. FT logic diagram of unavailability of integrated RO–FO system.

$$f_{\max}(x) = \begin{cases} x, & 0 \le x \le 1 \\ 0, & otherwise \end{cases} \tag{10}$$

$$f_{\min}(x) = \begin{cases} 1-x, & 0 \le x \le 1 \\ 0, & otherwise \end{cases} \tag{11}$$

$$\text{FPS}_R(M) = \sup_x [f_M(x) \wedge f_{\max}(x)] \tag{12}$$

$$\text{FPS}_L(M) = \sup_x [f_M(x) \wedge f_{\min}(x)] \tag{13}$$

$$\text{FPS}_T(M) = [\text{FPS}_R(M) + 1 - \text{FPS}_L(M)] / 2 \tag{14}$$

The fuzzy number and its corresponding failure possibility scores of the fuzzy events shown in Table 2.

Step 5: Transform FPS into FFR, in order to integrate both failure rate and estimate the unavailability of the integrated RO–FO system using Eq. (9). The failure possibility scores of the fuzzy events and its corresponding FFRs are shown in Table 2.

Step 6: Calculate the unavailability of the subsystem of the integrated network from estimated failure rates.

4.2. Calculation of reliability indices of integrated system

Based on the above failure rate data, the unavailability of the subsystem was calculated in the following sections.

4.2.1. Seawater pump

Seawater pump supplied the entire feed to the FO system, hence, when seawater pump failed, the system was down. Based on the calculated failure rate given in Tables 1 and 2, the unavailability of the seawater pump was calculated from the top down event of FTA and using Eqs. (1) and (2).

$$\overline{A}_{\text{sw}} = 7.25 \times 10^{-4} \tag{15}$$

4.2.2. Pretreatment system

The unavailability of the filter was zero:

$$\overline{A}_{\text{filter}} = 0 \tag{16}$$

4.2.3. FO stage

Since two trains of FO modules were taken in series, the unreliability of the trains was to be multiplied to get the unreliability of the FO subsystem. In addition, brine stream of RO subsystem is pump to FO subsystem and considered as high salinity stream in FO stage. From the FFR data on the two trains, the unavailability was determined as follows:

$$\overline{A}_{\text{FO}} = 1.78 \times 10^{-3} \tag{17}$$

4.2.4. RO stage

RO stage of the system was comprised of an HPP, membrane module and stream to FO stage. The unavailability of the each of the items of RO stage was determined as follows:

$$\overline{A}_{\text{RO}} = 0.0132 \tag{18}$$

Table 1
Failure rate data for hybrid system

Failure events	Failure rate/year
1,111	2.45×10^{-4}
11,141	7.52×10^{-5}
11,142	6.51×10^{-5}
11,151	7.06×10^{-5}
11,152	2.26×10^{-4}
11,211	7.19×10^{-4}
11,212	7.42×10^{-4}
1,311	0.01303

Table 3
Ranking of various subsystem of integrated RO–FO system

Fault event	Code	Availability/h
RO stage	13	0.9868
HPP	1,311	0.9870
FO stage	14	0.9982
Dosing pump	122	0.9986
Seawater intake	11	0.99927
RO membrane	1,312	0.99981
FO membrane	1,412	0.99983
Filter	121	1.000

Table 2
Converting fuzzy numbers into fuzzy failure rate

Failure events/elements	1,112	1,113	11,143	113	1,312	1,412	1,122
FPS_R(M)	0.275	0.384	0.237	0.196	0.315	0.305	0.176
1-FPS_L(M)	0.055	0.064	0.0515	0.049	0.063	0.061	0.049
FPS_T(M)	0.165	0.224	0.1442	0.122	0.189	0.183	0.113
FFR	1.12×10^{-4}	3.31×10^{-4}	6.91×10^{-5}	3.71×10^{-5}	1.86×10^{-4}	1.65×10^{-4}	2.69×10^{-5}

4.2.5. Overall system reliability

The overall unavailability of the integrated RO–FO system was determined by applying Eq. (15).

$$\overline{A}_{\text{Plant}} = 1-(1-\overline{A}_{\text{sw}})\times(1-\overline{A}_{\text{pretreatment}})\times(1-\overline{A}_{\text{FO}})\times(1-\overline{A}_{\text{RO}}) \quad (19)$$

$$\overline{A}_{\text{Plant}} = 0.0156 \quad (20)$$

The availability of the integrated RO–FO desalination system is approximately 0.9844/h. The availability of the system appears to be high due to significant improvement in integrated RO–FO desalination system. Table 3 presents the most dominant fault paths based on their contribution to the top event and sorting in increasing order of availability. These fault events represent the potential areas for improvement. The most likely cause is RO stage, which include RO membrane module and brine stream to FO, followed by HPP. Thus, the improvement of failure occurrence of the two events will have the most significant contribution to enhance system safety and reliability. While installing a new plant, engineers and plant operators needed to keep the record of these two fault events in priority level and safety interventions are proposed as follows:

- The plant operators should focus on the investigation of the noise sources and external leakages of the HPP. They can install an intelligent self-diagnose system to protect the system from noises.
- The membrane module should maintained and perform regular cleaning to protect from fouling.

This approach resolves some problems in traditional method to estimate the failure rate of human performance. The method is simple and intuitive in terms of evaluation and computation. The analyst can give more reliable failure assessment and can evaluate the failure events directly using linguistic terms. The scarcity of objective and quantitative data on human performance in integrated RO–FO desalination system is a serious limitation. The failure probability represents the best judgment based on expert's opinion. However, this study gives a more flexible and appropriate function structure to combine objective and subjective events to reflect the diverse conditions in many industrial environments.

5. Conclusion

The RO is a major process for producing potable water from seawater through desalination. The performance of any desalination system depends on the failure behavior of its subsystems. Since the hybrid RO–FO system was proposed as power saving system, the reliability of the subsystems of RO and FO is to be maintained at a high level by proper design and selection of materials of these subsystems for operating in the continuous plant. Thus, in this study, a hybrid FTA method based on fuzzy set theory was used to directly estimate the failure probability, the FFR and availability of the system and provide the reliability information to the safety engineers to easily evaluate the failure rate of the top event.

Since integrated system showed very high availability, this integrated system can become viable to an alternative to single RO desalination plants used globally. The design of integrated RO–FO system is recommended because it has high performance, low power consumption and economically feasible.

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