Sewage Treatment Facility Maintenance: A Risk-based Approach for High-rise Residential Property

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Abstract. Although fuzzy-failure modes and effects analysis (Fuzzy-FMEA) is one of the risk-based maintenance approaches that has been used to devise or to improve an existing preventive maintenance program in various industries and settings, applying the technique in the context of sewage treatment facility (STF) is lacking. The proponent investigated the cause of failing effluent parameters of a high-rise residential property through the combination of the Ishikawa Diagram and 5-Whys, then the technique was applied and improved using the data gathered from qualified respondents with different exposure, and background, among others who answered 10-fuzzy scales regarding the severity, occurrence, and detectability of each failure modes, and ranked the importance of each chamber of an SBR-type STF. Results revealed that the Refined FRPN values emphasized the failure modes with relevance to each other by obtaining values within their functional counterparts resulting in a more apt categorization and prioritization than the FRPN. The paper shows that Fuzzy-FMEA is successful in devising a risk-based approach for SBR-type STF for high-rise residential property with an effective means of addressing the aggravating effluent parameters in the maintenance aspect to comply with the Philippine Department of Environment and Natural Resources (DENR) Department Administrative Order (DAO) 2016-08.

1 Introduction

1.1 Non-Compliance of High-rise Residential Property to Regulatory Requirements

Multi-story buildings can be categorized as high-rise, mid-rise, low-rise, skyscraper, super-tall, and mega-tall [1]. In an urban setting, like Quezon City where land use is of utmost consideration, residential developments are more inclined toward high-rise properties, or greater. With the increase in demand for high-rise residential properties, so has the demand for sewage treatment.

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In the Philippines, high-rise residential properties are bound under the statutory regulations of Republic Act 9275 [2] also known as the Clean Water Act of 2004. Furthermore, a regulatory requirement set by the Department of Environment and Natural Resources known as DENR Administrative Order 2016-08 [3] requires the compliance of the property to the general effluent standards. Significant parameters covered in DAO 2016-08 under PSIC Code 681 (Real Estate Activities) include biochemical oxygen demand (BOD), Fecal Coliform, Ammonia, Nitrate, Phosphate, Oil and Grease, and Surfactants.

In the 18th WEPA Meeting concerning the updates on Industrial Wastewater Management in the Philippines, Uyaco [4] reported a total of 932 inspected establishments that were issued with Notice of Violations (NOVs) and Cease and Desist Order (CDO) from 2014 to 2019 for establishments under the jurisdiction of the LLDA. On the other hand, in the establishments inspected under the jurisdiction of DENR in the year 2020-2021, a sum of 3,205 was issued with NOVs, and 1,718 surveyed establishments operating without permits. To synthesize, high-rise residential properties are contributors to these numbers.

Failing to comply with the effluent parameters is subject to a fine amounting to PHP 10,000.00 to PHP 200,000.00 per day of violation and subjected to a 10% increase every two (2) years due to inflation under Laguna Lake Development Authority (LLDA) Memorandum Circular (MC) No. 2017-05 [5]. Aside from the environmental risk to the nearby bodies of water, the site is also at risk of financial losses

1.2 Relevance of Risk in a Sequencing Batch Reactor Type Sewage Treatment Facility

The SBR-type STF is the most appropriate sewage treatment technology for multi-storied buildings in comparison to Membrane Bio Reactor (MBR), Extended Aeration (EA), and Fluidized Bed Bio Reactor (FBBR) [6]. The features of SBR-type STF such as cyclical time-sequence operation, space- and environment-friendly made it an attractive technology for sewage treatment [7]. However, the one-tank design and setup simplicity has a drawback when the equipment is not maintained properly. Sewerage consists of a wide variety of harmful substances such as sludge, dioxins, furans, polychlorinated biphenyls, organochlorine insecticides, absorptive and derived chlorine derivatives, polycyclic aromatic hydrocarbons, phenols, and their derivatives, phthalates, and others [8]. Consequently, an SBR chamber is classified as a confined space as it is large enough for an individual to enter and perform work, not designed for human occupancy, and has limited entry or exit, meeting the three (3) criteria stated by Hodgson [9]. Hence, there is a considerable risk in operating an SBR-type STF.

1.3 Root Cause for Failing Effluent Parameters

To address the issue of aggravating effluent parameters, a high-rise property was surveyed to determine its root cause. It was confirmed that in the year 2021, significant parameters such as ammonia, oil and grease, phosphate, and fecal coliform were failing (see Fig. 1).

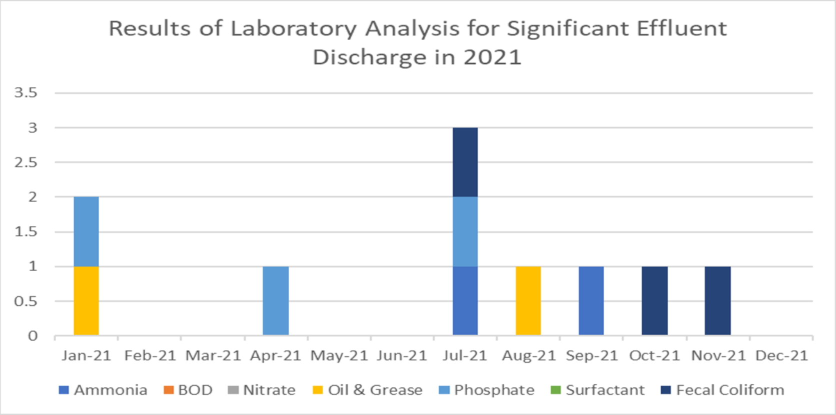


Fig. 1. Results of Laboratory Analysis for Significant Effluent Discharge in Year 2021

Aside from the significant parameters, it was also noted that other general effluent parameters were also failings. These are chemical oxygen demand (COD), pH, total suspended solids (TSS), and total coliform (see Fig. 2). These parameters, though not significant, could impact the nearby body of water to where the effluent is being discharged. Records for May and June 2021 were not recorded due to any of the possible factors: missing documents, and work restrictions brought about by the COVID-19 pandemic, among others.

The actual site survey reveals an ineffective approach as evaluated in the root cause analysis using the combination of the Ishikawa-5 Why technique (see Fig. 3). In service-level agreements between an end-user and a service provider, maintenance records should be safely kept and properly archived. However, this was not the case for the surveyed site. Sockeye suggests the indicators of ineffective maintenance are constant equipment malfunction, and a heavy amount of unplanned work [10], among others, whereas the surveyed site exhibited missing documents, missed logs, visible equipment deterioration, and prolonged downtime of critical machinery. With the considerable risk in operating an SBR type STF, and the underlying issue of ineffective maintenance, the possible solution of incorporating risk in the maintenance aspect of the sewage treatment facility operations is considered by employing risk-based maintenance.

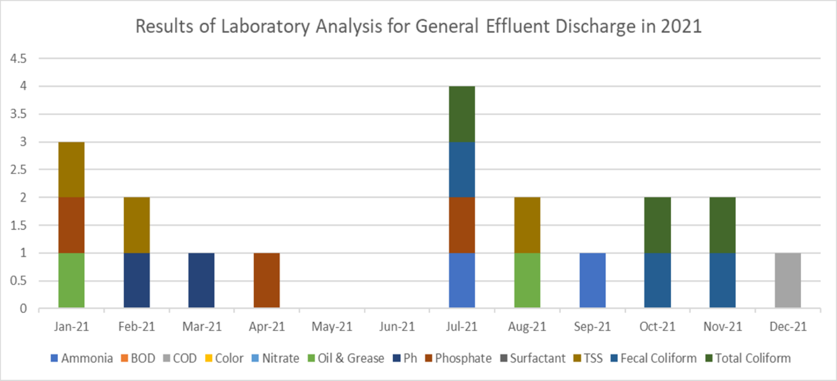


Fig. 2. Results of Laboratory Analysis for General Effluent Discharge in Year 2021

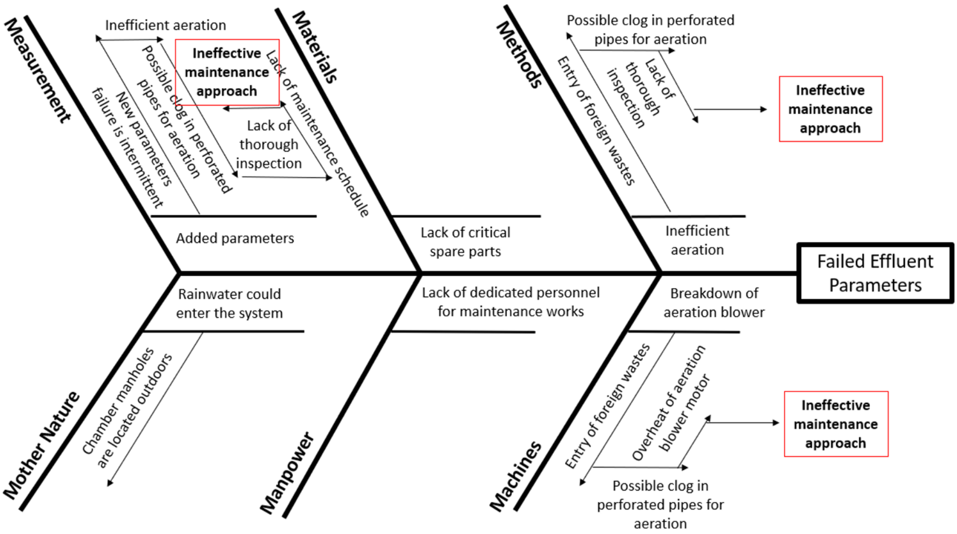


Fig. 3. Root-cause Analysis for Failed Effluent Parameters using Combined Ishikawa-Why's Diagram

1.4 Risk-based Maintenance

1.4.1 Aggravating effluent parameters

Maintenance ensures the functionality of equipment, or a system while risk means exposure to harm. Operating an SBR-type STF exposes a property to risk due to harmful by-products that may form due to chemical reactions such as anaerobic digestion. Risk-based maintenance is an approach to preventive maintenance where risk is the input for maintenance-decision making. This approach has been utilized in different industries such as turbomachinery [11], semi-conductor [12], medical devices [13], public school facilities [14], pipe inspections [15], manufacturing [16], public water treatment plants [17], petrochemical [18], automotive [19], and industrial companies [20] to improve their maintenance strategy.

In RBM, maintenance activities are categorized after a series of processes like risk identification, and risk evaluation where the high levels of unacceptable risk are to be prioritized by employing dedicated maintenance activity exclusive for the risk, frequent inspection, and other means of control to lower the risk that is acceptable to the end-user and for the continuity of the operation. Moreover, different methodologies can be applied depending on the available data making RBM employable to any topic. The quantitative approach [21], genetic algorithm [22], and failure modes, effects, and criticality analysis [17] are some of the related studies employing the methodology compatible with RBM. The widely used methodology is the failure modes and effects analysis (FMEA) with applications in water utility sector [23], food industry [24], oil industry [25], medical industry [26], and geothermal plants [27], among others.

The FMEA as the methodology for RBM employs the use of ordinal data to level the magnitude of risk in terms of different risk factors such as severity, occurrence, and detectability. It starts by identifying the failure modes of a system, and then evaluating each failure mode in terms of the risk factors based on how it would affect the system. After evaluating a failure mode in terms of the risk factors, a priority number will be determined, and compare how it will be compared with other priority numbers of other failure modes. The decision-making comes when all the failure modes obtain their corresponding risk priority number (RPN). However, due to the simple algorithm, multiple failure modes could have the same priority number and it is listed as one of the shortcomings and limitations of the FMEA (or traditional FMEA) [28-29].

The likes of Kirkire et al. [30] then developed the Fuzzy-FMEA where the algorithm became more complex by integrating computational intelligence brought about by fuzzy logic. A study by Soltanali et al. [19] explored the Fuzzy-FMEA approach by employing different combinations of fuzzy scale (3-point fuzzy scale, 5-point fuzzy scale, 10-point fuzzy scale), fuzzification method (gaussian, and pi, among others), and defuzzification method (centroid, among others) to attain the fuzzy risk priority number (FRPN). It was revealed that the 10-point fuzzy scale holds significance in attaining the most credible results in comparison with 3-point and 5-point fuzzy scales, and neither the fuzzification method nor the defuzzification method has any significance in the result which means employing any method in the fuzzy logic should do.

Despite the application of RBM in different industries, there is a lack of research applying the methodology in the context of STF. Since the SBR-type STF has different sections (or chambers), this study considers the importance of each section and incorporates the same into the RBM to further improve the Fuzzy-FMEA technique. In this way, the issue of aggravating effluent parameters to the surveyed site could be addressed and consequently, mitigate the discharge of mistreated effluent to the environment.

1.5 Objective

The objective of this paper is to devise a RBM approach for SBR-type STF to address the issue of discharging mistreated effluent in the environment brought about by failing effluent parameters of high-rise residential properties.

2 Materials and Methods

2.1 Identification of Failure Modes

A thorough evaluation of the system was conducted to identify the relevant failure modes. The failure modes were identified by examining the machinery and auxiliaries employed in the SBR-type STF chambers. The machinery and auxiliaries found in the chambers include submersible pumps, submersible aeration blowers, the motor control center, coarse bubble diffusers, fine bubble diffusers, wastewater piping, air pipelines, and piping supports, among others.

The components were classified into mechanical, electrical, and auxiliaries. The failure modes for mechanical components are as follows: for the submersible pump, the study of Oluwatoyin et al. [31] about the failure modes of the submersible pump was utilized while for the aeration blowers, due to the lack of available literature, the actual equipment manual [32] was reviewed to determine the failure modes of relevant components. The failure modes of compact mechanical components were generalized to fail like the chlorinator pump failure. Also, the failure modes for electrical components were identified by analyzing the single-line diagram of the system. The limitation of the failure modes for electrical components was the feeder line for the motor control center. Finally, the failure modes for auxiliary components were identified by analyzing the process flow diagram of the system (see Fig. 4).

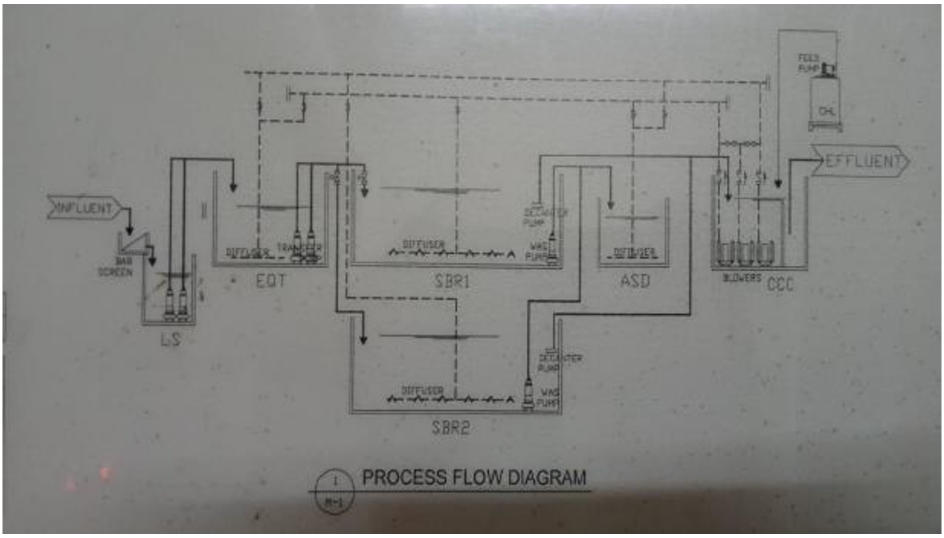


Fig. 4. Process flow diagram of the SBR-type STF.

2.2 Population, Sample Size, and Consensus Value

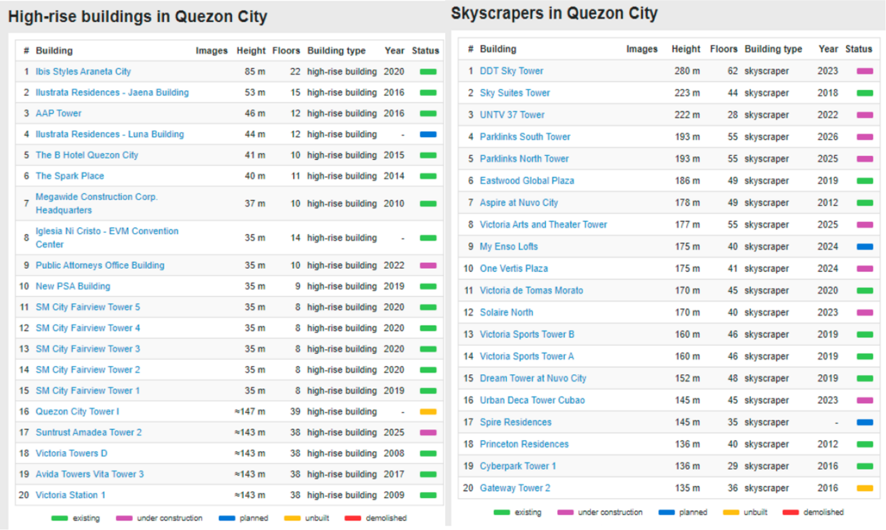
The FMEA technique requires opinions from qualified individuals about the level of the risk factors. In this study, the issue of aggravating effluent parameters brought about by the ineffective maintenance approach was generalized to high-rise residential properties, and skyscrapers in the locality of Quezon City since it is the largest city in the Philippines [33]. Secondary data from Emporis [34] was used to quantify the number of high-rise properties, and skyscrapers then refined in accordance to the following: a) the property must have already been built, operating, or existing at the time of study, b) the property must have residential or condominium usage, c) the multi-development properties were considered to have centralized STF.

The sample size can then be computed using the Cochran's formula:

$$n = \frac{\frac{z^2(p)(1-p)}{e^2}}{1+\left(\frac{z^2(p)(1-p)}{e^2 N}\right)} \quad (1)$$

Where n is the number of samples, N is the total population, e is error tolerance (level) or margin of error (0.05), p is the sample proportion, and z is the z-value found in Z-score Table.

The sample size corresponds to the minimum number of qualified individuals required for the study. The qualification includes: a) at least a bachelor's degree in a relevant engineering discipline such as mechanical engineering, electrical engineering, chemical engineering, sanitary engineering, environmental engineering, and other allied disciplines, b) exposure to an SBR-type STF during the design, construction, operation, maintenance, audit, and testing and commissioning.



High-rise buildings in Quezon City

#	Building	Images	Height	Floors	Building type	Year	Status
1	Ibis Styles Araneta City		85 m	22	high-rise building	2020	🟩
2	Ilustrata Residences - Jaena Building		53 m	15	high-rise building	2016	🟩
3	AAP Tower		46 m	12	high-rise building	2016	🟩
4	Ilustrata Residences - Luna Building		44 m	12	high-rise building	-	🟦
5	The B Hotel Quezon City		41 m	10	high-rise building	2015	🟩
6	The Spark Place		40 m	11	high-rise building	2014	🟩
7	Megawide Construction Corp. Headquarters		37 m	10	high-rise building	2010	🟩
8	Iglesia Ni Cristo - EVM Convention Center		35 m	14	high-rise building	-	🟩
9	Public Attorneys Office Building		35 m	10	high-rise building	2022	🟪
10	New PSA Building		35 m	9	high-rise building	2019	🟩
11	SM City Fairview Tower 5		35 m	8	high-rise building	2020	🟩
12	SM City Fairview Tower 4		35 m	8	high-rise building	2020	🟩
13	SM City Fairview Tower 3		35 m	8	high-rise building	2020	🟩
14	SM City Fairview Tower 2		35 m	8	high-rise building	2020	🟩
15	SM City Fairview Tower 1		35 m	8	high-rise building	2019	🟩
16	Quezon City Tower I		≈147 m	39	high-rise building	-	🟨
17	Suntrust Amadea Tower 2		≈143 m	38	high-rise building	2025	🟪
18	Victoria Towers D		≈143 m	38	high-rise building	2008	🟩
19	Avida Towers Vita Tower 3		≈143 m	38	high-rise building	2017	🟩
20	Victoria Station 1		≈143 m	38	high-rise building	2009	🟩

🟩 existing 🟪 under construction 🟦 planned 🟨 unbuilt 🟥 demolished

Skyscrapers in Quezon City

#	Building	Images	Height	Floors	Building type	Year	Status
1	DDT Sky Tower		280 m	62	skyscraper	2023	🟪
2	Sky Suites Tower		223 m	44	skyscraper	2018	🟩
3	UNTV 37 Tower		222 m	28	skyscraper	2022	🟪
4	Parklinks South Tower		193 m	55	skyscraper	2026	🟪
5	Parklinks North Tower		193 m	55	skyscraper	2025	🟪
6	Eastwood Global Plaza		186 m	49	skyscraper	2019	🟩
7	Aspire at Nuvo City		178 m	49	skyscraper	2012	🟩
8	Victoria Arts and Theater Tower		177 m	55	skyscraper	2025	🟪
9	My Enso Lofts		175 m	40	skyscraper	2024	🟦
10	One Vertis Plaza		175 m	41	skyscraper	2024	🟪
11	Victoria de Tomas Morato		170 m	45	skyscraper	2020	🟩
12	Solaire North		170 m	40	skyscraper	2023	🟪
13	Victoria Sports Tower B		160 m	46	skyscraper	2019	🟩
14	Victoria Sports Tower A		160 m	46	skyscraper	2019	🟩
15	Dream Tower at Nuvo City		152 m	48	skyscraper	2019	🟩
16	Urban Deca Tower Cubao		145 m	45	skyscraper	2023	🟪
17	Spire Residences		145 m	35	skyscraper	-	🟦
18	Princeton Residences		136 m	40	skyscraper	2012	🟩
19	Cyberpark Tower 1		136 m	29	skyscraper	2016	🟩
20	Gateway Tower 2		135 m	36	skyscraper	2016	🟨

🟩 existing 🟪 under construction 🟦 planned 🟨 unbuilt 🟥 demolished

Fig. 5. Sample list a) high-rise buildings, and b) skyscrapers in Quezon City.[34]

Various scholars suggest employing median or mode as the measure of central tendency for ordinal data [35-38]. Hence, for the consensus values for the importance ranking of chambers and determining the magnitude of the risk factors, either median or mode was used.

The qualified respondents expressed their opinions on the risk factors: severity, occurrence, and detectability of each failure mode using a 10-point Fuzzy scale to have credible results [18]. Linguistic terms range from Very Low to Extremely High. Severity and occurrence have the very low scale as the lowest, while the extremely high scale is the highest. Detectability, on the other hand, was reversed being very low as the highest, while extremely high as the lowest. The consensus values for risk factors were the central tendencies median or mode, whichever was fitter to represent the population.

2.3 Chamber Relative Importance and Weighted Importance of the Failure Mode

The qualified respondents expressed their opinions about the chamber's relative importance: lift station (LS), equalization tank (EQT), sequencing batch reactor (SBR), aerobic sludge digester (ASD), and chlorine contact chamber (CCC), using a 5-point Likert scale where 1 is the least important and 5 is the most important. To determine their weighted importance, the weighted average method was employed.

$$LS_i = 0.1(f_{LTI}) + 0.2(f_{LRI}) + 0.3(f_I) + 0.4(f_{MRI}) + 0.5(f_{MTI}) \quad (2)$$

$$EQT_i = 0.1(f_{LTI}) + 0.2(f_{LRI}) + 0.3(f_I) + 0.4(f_{MRI}) + 0.5(f_{MTI}) \quad (3)$$

$$SBR_i = 0.1(f_{LTI}) + 0.2(f_{LRI}) + 0.3(f_I) + 0.4(f_{MRI}) + 0.5(f_{MTI}) \quad (4)$$

$$ASD_i = 0.1(f_{LTI}) + 0.2(f_{LRI}) + 0.3(f_I) + 0.4(f_{MRI}) + 0.5(f_{MTI}) \quad (5)$$

$$CCC_i = 0.1(f_{LTI}) + 0.2(f_{LRI}) + 0.3(f_I) + 0.4(f_{MRI}) + 0.5(f_{MTI}) \quad (6)$$

Where LS is the lift station, EQT is the equalization tank, SBR is the sequencing batch reactor, ASD is the aerobic sludge digester, CCC is the chlorine contact chamber, f is the frequency, LTI is least important, LRI is lesser important, I is important, MRI is more important, and MTI is most important

The failure mode of a component could not be present in all chambers. In that regard, the presence of each failure mode was evaluated on a per-chamber basis. Hence, The FRPN value was further processed by incorporating the weighted importance of each failure mode. The sum of the weighted importance to where the failure mode was present determines the failure mode's weighted importance. The assigned addend for the least important chamber is 1, for the lesser important chamber is 2, important chamber is 3, more important chamber is 4, and the most important chamber is 5. If a failure mode is present in all chambers, then its weighted importance is 15. If a failure mode is not present in such chamber, the assigned value as addend is 0.

$$WIFM_n = LS_n + ET_n + SBR_n + ASD_n + CCC_n \quad (7)$$

Where WIFM is the weighted importance of failure mode, LS is the lift station, ET is the equalization tank, SBR is the sequencing batch reactor, ASD is the aerobic sludge digester, CCC is the chlorine contact chamber, and n is the corresponding failure mode.

2.4 RBM Methodology

The outputs of the main processes of the RBM methodology are priority numbers: risk priority number (RPN), Fuzzy Risk Priority Number (FRPN), and Refined Fuzzy Risk Priority Number (Refined FRPN). The values were processed in an iterative way [39].

2.4.1 Risk Priority Number (RPN)

The RPN is the product of the risk factors: severity, occurrence, and detectability. The formula for RPN is:

$$RPN = S \times O \times D \quad (8)$$

Where RPN is the risk priority number, S is the severity, O is the occurrence, and D is the detectability. The value for each risk factor follows the value set in the consensus values for risk factors.

2.4.2 Fuzzy Risk Priority Numbers (FRPN)

The FRPN utilized the median or mode as the consensus value for each failure mode as input. The processes were subdivided into three (3): fuzzification, fuzzy inference system, and defuzzification.

The first process involved the Gaussian Membership Function (gaussmf) as the fuzzification method with the standard deviation of the corresponding consensus value as the fuzzy number in the input. This is when the consensus values obtain their corresponding fuzzy number and the notation is as follows ($\sigma_{S,O,D}$, $CV_{S,O,D}$) where σ is the standard deviation, and CV is a crisp value from 1-10 with intervals of 1. See Table 1 for the breakdown of the linguistic terms, and their corresponding fuzzy numbers for risk factors.

Table 1. Linguistic Terms and their Corresponding Fuzzy Numbers for Risk Factors

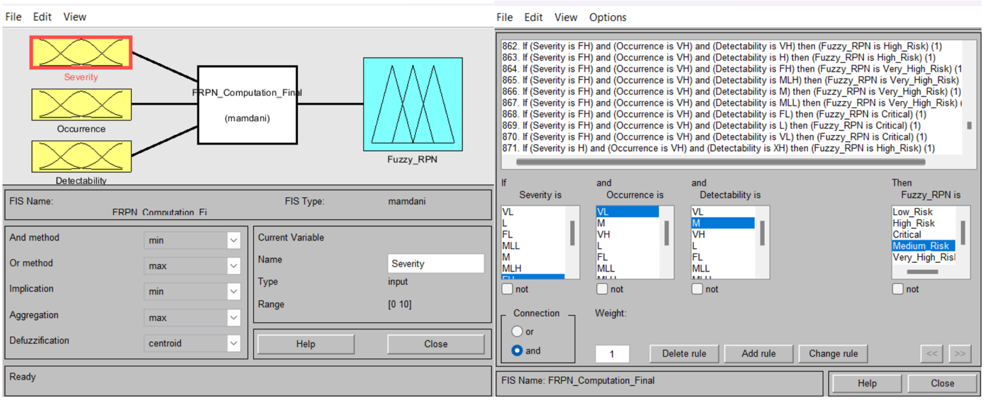
Fuzzy Numbers for Risk Factors			
Linguistic Term	*Severity, S*	*Occurrence, O*	*Detectability, D*
	(σ_{S},, CV_S)	(σ_O, CV_O)	(σ_D, CV_D)
Very Low, VL	(σ_{S},, 1)	(σ_O, 1)	(σ_D, 10)
Low, L	(σ_{S},, 2)	(σ_O, 2)	(σ_D, 9)
Fairly Low, FL	(σ_{S},, 3)	(σ_O, 3)	(σ_D, 8)
More or Less Low, MLL	(σ_{S},, 4)	(σ_O, 4)	(σ_D, 7)
Medium, M	(σ_{S},, 5)	(σ_O, 5)	(σ_D, 6)
More or Less High, MLH	(σ_{S},, 6)	(σ_O, 6)	(σ_D, 5)
Fairly High, FH	(σ_{S},, 7)	(σ_O, 7)	(σ_D, 4)
High, H	(σ_{S},, 8)	(σ_O, 8)	(σ_D, 3)
Very High, VH	(σ_{S},, 9)	(σ_O, 9)	(σ_D, 2)
Extremely High, XH	(σ_{S},, 10)	(σ_O, 10)	(σ_D, 1)

The second process was the Mamdani Fuzzy Inference System (Mamdani FIS) as the inference system. This is when the consensus values of the risk factors, together with their corresponding fuzzy number, were evaluated based on the 1000 rules inputted in the Mamdani FIS. See Table 2 for the sample of rules for the computation of FRPN, Fig. 6a for the MATLAB interface of the Fuzzy Logic Designer for FRPN, Fig. 6b for the MATLAB interface of rules, Fig. 7a for the MATLAB interface for the input variable "Severity", Fig. 7b for the MATLAB interface for the input variable "Occurrence", and Fig. 8a for the MATLAB interface for the input variable "Detectability".

Table 2. Sample Rules for the Computation of FRPN

Fuzzy Numbers for Risk Factors							
Rule No.	*Severity, S*	*and*	*Occurrence, O*	*and*	*Detectability, D*	*then*	*FRPN*
1	VL	*and*	VL	*and*	XH	*then*	Low Risk
66	FH	*and*	VL	*and*	M	*then*	Medium Risk
330	FL	*and*	MLL	*and*	VL	*then*	High Risk
640	MLL	*and*	FH	*and*	VL	*then*	Very High Risk
868	FH	*and*	VH	*and*	FL	*then*	Critical

The third process was the centroid as the defuzzification method where the curve of severity, occurrence, and detectability were merged in consideration with the rules inputted in the Mamdani FIS. The point to which the centroid was located was the FRPN of the failure mode. The notation is as follows (RPN, FRPN) where RPN is the risk priority number, and FRPN is a crisp value from 1-1000 with intervals of 200 with (RPN, 100) as low risk, (RPN, 300) as medium risk, (RPN, 500) as high risk, (RPN, 700) as very high risk, (RPN, 900) as a critical. See Fig. 8b for the MATLAB interface for the output variable "Fuzzy RPN", and Fig. 9 for the MATLAB interface for the computation of Fuzzy RPN.

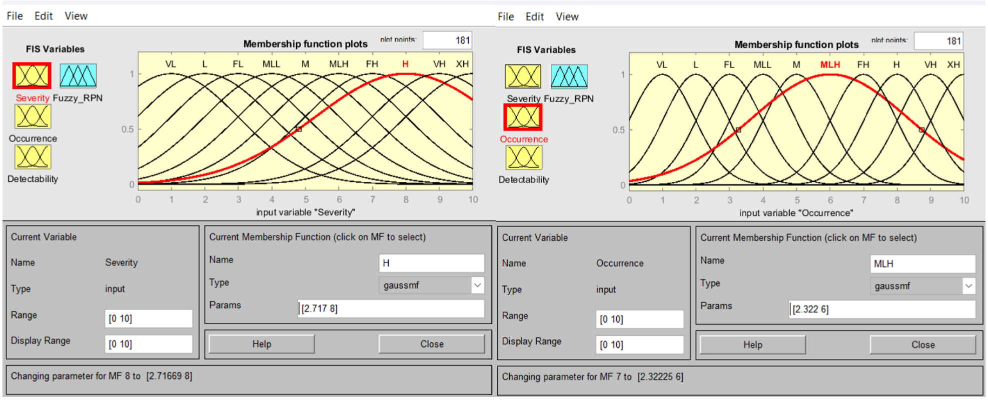


FIS Name: FRPN_Computation_Fi
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
Current Variable
Name: Severity
Type: input
Range: [0 10]
Ready

```
862. If (Severity is FH) and (Occurrence is VH) and (Detectability is VH) then (Fuzzy_RPN is High_Risk) (1)
863. If (Severity is FH) and (Occurrence is VH) and (Detectability is H) then (Fuzzy_RPN is High_Risk) (1)
864. If (Severity is FH) and (Occurrence is VH) and (Detectability is FH) then (Fuzzy_RPN is Very_High_Risk) (1
865. If (Severity is FH) and (Occurrence is VH) and (Detectability is MLH) then (Fuzzy_RPN is Very_High_Risk)
866. If (Severity is FH) and (Occurrence is VH) and (Detectability is M) then (Fuzzy_RPN is Very_High_Risk) (1)
867. If (Severity is FH) and (Occurrence is VH) and (Detectability is MLL) then (Fuzzy_RPN is Very_High_Risk) (
868. If (Severity is FH) and (Occurrence is VH) and (Detectability is FL) then (Fuzzy_RPN is Critical) (1)
869. If (Severity is FH) and (Occurrence is VH) and (Detectability is L) then (Fuzzy_RPN is Critical) (1)
870. If (Severity is FH) and (Occurrence is VH) and (Detectability is VL) then (Fuzzy_RPN is Critical) (1)
871. If (Severity is H) and (Occurrence is VH) and (Detectability is XH) then (Fuzzy_RPN is High_Risk) (1)
```

If Severity is: VL, L, FL, MLL, M, MLH; ☐ not
and Occurrence is: VL, M, VH, L, FL, MLL; ☐ not
and Detectability is: VL, M, VH, L, FL, MLL; ☐ not
Then Fuzzy_RPN is: Low_Risk, High_Risk, Critical, Medium_Risk, Very_High_Risk; ☐ not
Connection: ○ or ● and
Weight: 1
FIS Name: FRPN_Computation_Final

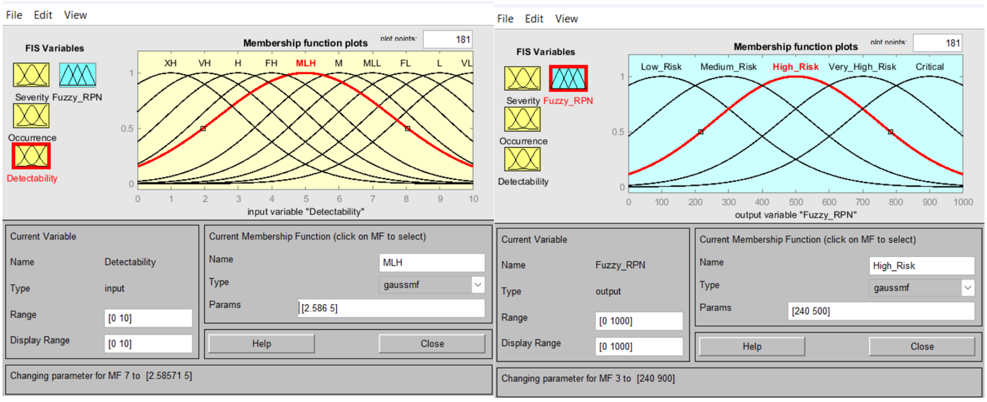
Fig. 6. MATLAB interface for the a) Fuzzy Logic Designer for FRPN, b) 1000 rules inputted in the Mamdani FIS



Current Variable
Name: Severity
Type: input
Range: [0 10]
Display Range: [0 10]
Current Membership Function (click on MF to select)
Name: H
Type: gaussmf
Params: [2.717 8]
Changing parameter for MF 8 to [2.71669 8]

Current Variable
Name: Occurrence
Type: input
Range: [0 10]
Display Range: [0 10]
Current Membership Function (click on MF to select)
Name: MLH
Type: gaussmf
Params: [2.322 6]
Changing parameter for MF 7 to [2.32225 6]

Fig. 7. MATLAB interface for the input variables a) Severity, and b) Occurrence



Current Variable
Name: Detectability
Type: input
Range: [0 10]
Display Range: [0 10]

Current Membership Function (click on MF to select)
Name: MLH
Type: gaussmf
Params: [2.586 5]

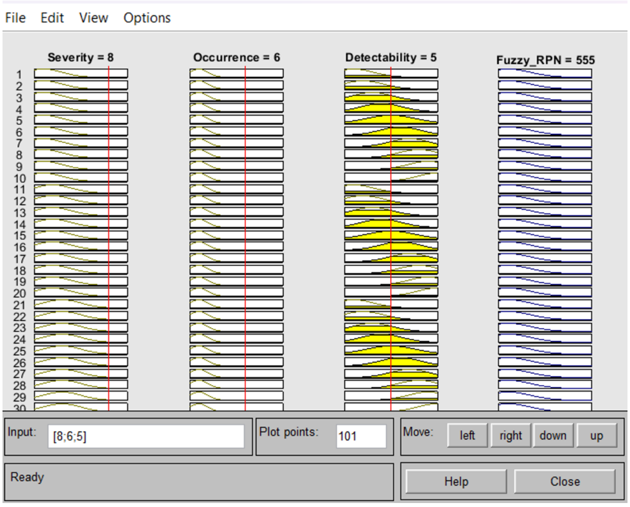
Changing parameter for MF 7 to [2.58571 5]

Current Variable
Name: Fuzzy_RPN
Type: output
Range: [0 1000]
Display Range: [0 1000]

Current Membership Function (click on MF to select)
Name: High_Risk
Type: gaussmf
Params: [240 500]

Changing parameter for MF 3 to [240 900]

Fig. 8. MATLAB interface for the a) input variable "Detectability" and, b) the output variable "Fuzzy RPN".



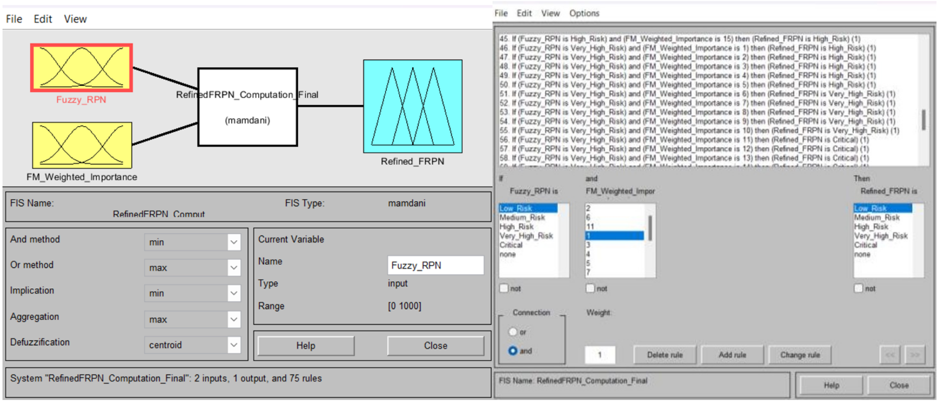
Severity = 8
Occurrence = 6
Detectability = 5
Fuzzy_RPN = 555

Input: [8;6;5]
Plot points: 101
Ready

Fig. 9. MATLAB interface for the computation of Fuzzy RPN (FRPN)

2.4.3 Refined Fuzzy Risk Priority Numbers (Refined FRPN)

The process of obtaining the Refined FRPN was subdivided into three (3): fuzzification, fuzzy inference system, and defuzzification. The first process involved the fuzzification method using gaussmf having FRPN and the WIFM as the inputs. For FRPN, the fuzzy number assigned is the uniform standard deviation of the RPN, and the crisp value is the FRPN. The notation is as follows: (σ_{RPN}, FRPN) where σ_{RPN} is the uniform standard deviation of the RPN, and FRPN is a crisp value from 100-900 with intervals of 200. For WIFM, the fuzzy number assigned is the uniform standard deviation of the WIFM, and the crisp value is WIFM. The notation is as follows: (σ_{WIFM}, WIFM) where σ_{WIFM} is the uniform standard deviation of WIFM, and WIFM is a crisp value from 1-15 with intervals of 1. Fig. 10a shows the MATLAB interface for the Fuzzy Logic Designer for Refined FRPN.



FIS Name: RefinedFRPN_Comput
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
Current Variable
Name: Fuzzy_RPN
Type: input
Range: [0 1000]

```
System "RefinedFRPN_Computation_Final": 2 inputs, 1 output, and 75 rules
```

```
45. If (Fuzzy_RPN is High_Risk) and (FM_Weighted_Importance is 15) then (Refined_FRPN is High_Risk) (1)
46. If (Fuzzy_RPN is Very_High_Risk) and (FM_Weighted_Importance is 1) then (Refined_FRPN is High_Risk) (1)
47. If (Fuzzy_RPN is Very_High_Risk) and (FM_Weighted_Importance is 2) then (Refined_FRPN is High_Risk) (1)
48. If (Fuzzy_RPN is Very_High_Risk) and (FM_Weighted_Importance is 3) then (Refined_FRPN is High_Risk) (1)
49. If (Fuzzy_RPN is Very_High_Risk) and (FM_Weighted_Importance is 4) then (Refined_FRPN is High_Risk) (1)
50. If (Fuzzy_RPN is Very_High_Risk) and (FM_Weighted_Importance is 5) then (Refined_FRPN is High_Risk) (1)
51. If (Fuzzy_RPN is Very_High_Risk) and (FM_Weighted_Importance is 6) then (Refined_FRPN is Very_High_Risk) (1)
52. If (Fuzzy_RPN is Very_High_Risk) and (FM_Weighted_Importance is 7) then (Refined_FRPN is Very_High_Risk) (1)
53. If (Fuzzy_RPN is Very_High_Risk) and (FM_Weighted_Importance is 8) then (Refined_FRPN is Very_High_Risk) (1)
54. If (Fuzzy_RPN is Very_High_Risk) and (FM_Weighted_Importance is 9) then (Refined_FRPN is Very_High_Risk) (1)
55. If (Fuzzy_RPN is Very_High_Risk) and (FM_Weighted_Importance is 10) then (Refined_FRPN is Very_High_Risk) (1)
56. If (Fuzzy_RPN is Very_High_Risk) and (FM_Weighted_Importance is 11) then (Refined_FRPN is Critical) (1)
57. If (Fuzzy_RPN is Very_High_Risk) and (FM_Weighted_Importance is 12) then (Refined_FRPN is Critical) (1)
58. If (Fuzzy_RPN is Very_High_Risk) and (FM_Weighted_Importance is 13) then (Refined_FRPN is Critical) (1)
```

Weight: 1

FIS Name: RefinedFRPN_Computation_Final

Fig. 10. MATLAB interface for the a) Fuzzy Logic Designer for Refined FRPN, b) 75 rules inputted in the Mamdani FIS

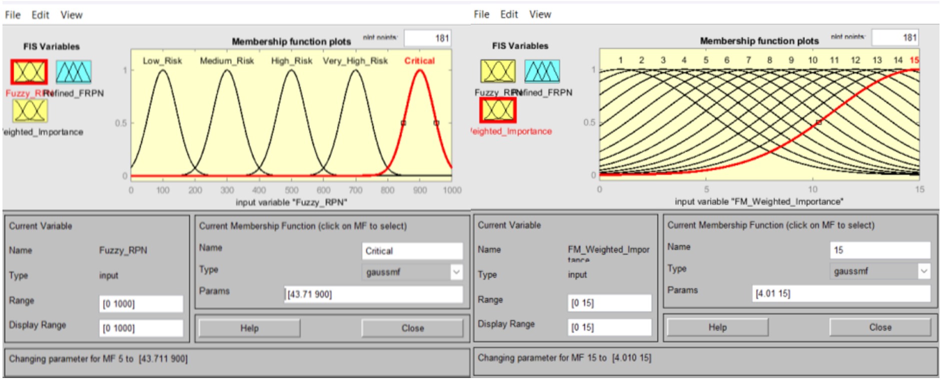
The second process was the Mamdani FIS as the inference system where the FRPN values' standard deviation and the failure modes' weighted importance were evaluated using a set of rules. Table 3 shows the sample rules for computation of Refined FRPN. Fig. 10b shows the MATLAB interface for the 75 rules inputted in the Mamdani FIS.

Table 3. Sample Rules for the Computation of Refined FRPN.

Fuzzy Numbers for Risk Factors					
Rule No.	*FRPN*	*and*	*Weighted Importance of Failure Mode*	*then*	*FRPN*
5	Low Risk	*and*	5	*then*	Low Risk
21	Medium Risk	*and*	6	*then*	Medium Risk
45	High Risk	*and*	15	*then*	High Risk
55	Very High Risk	*and*	10	*then*	Very High Risk
75	Critical	*and*	6	*then*	Critical

The third process was the centroid as the defuzzification method where the curve for FRPN and the weighted importance of the failure mode were merged considering the rule base inputted in the Mamdani FIS. The point to which the centroid was located is the Refined FRPN of the failure mode. The notation for the Refined FRPN is as follows: (σ_{RPN}, Refined FRPN) where σ_{RPN} is the uniform standard deviation of RPN, and Refined FRPN is a crisp value from 100-900 having intervals of 200 with (σ_{RPN}, 100) as low risk, (σ_{RPN}, 300) as medium risk, (σ_{RPN}, 500) as high risk, (σ_{RPN}, 700) as very high risk, and (σ_{RPN}, 900) as critical. Fig. 11a shows the MATLAB interface for the input variable "Fuzzy RPN", Fig. 11b shows the MATLAB interface for the input variable "Weighted Importance of Failure Mode", Fig. 12a shows the MATLAB interface for the output variable "Refined FRPN", and Fig. 12b shows the MATLAB interface for the computation for Refined FRPN.

The summary of the RBM methodology is reflected in Fig. 13. The materials used for acquiring, processing, and presenting the data are Google Forms, MS Excel, SPSS Statistics, MATLAB, and OriginPro8



Current Variable
Name Fuzzy_RPN
Type input
Range [0 1000]
Display Range [0 1000]

Current Membership Function (click on MF to select)
Name Critical
Type gaussmf
Params [43.71 900]

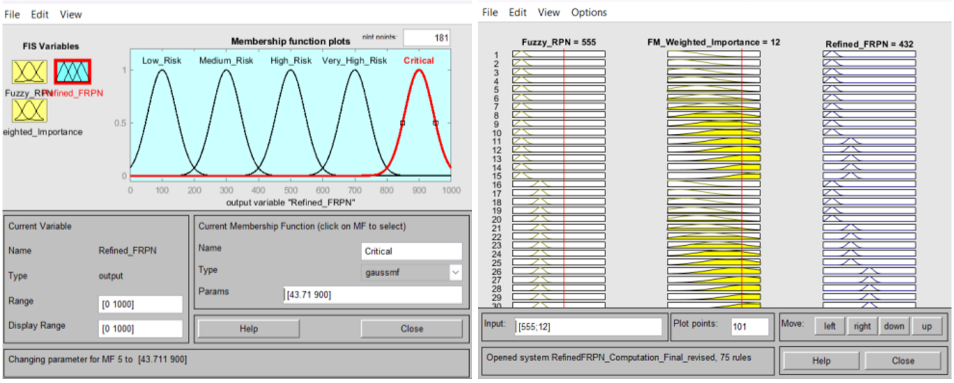
Changing parameter for MF 5 to [43.711 900]

Current Variable
Name FM_Weighted_Importance
Type input
Range [0 15]
Display Range [0 15]

Current Membership Function (click on MF to select)
Name 15
Type gaussmf
Params [4.01 15]

Changing parameter for MF 15 to [4.010 15]

Fig. 11. MATLAB interface for the input variable a) Fuzzy RPN and b) Weighted Importance of Failure Mode



Current Variable
Name Refined_FRPN
Type output
Range [0 1000]
Display Range [0 1000]

Current Membership Function (click on MF to select)
Name Critical
Type gaussmf
Params [43.71 900]

Changing parameter for MF 5 to [43.711 900]

Input: [555;12]
Plot points: 101

Opened system RefinedFRPN_Computation_Final_revised, 75 rules

Fig. 12. MATLAB interface for the a) output variable “Refined FRPN” b) computation for Refined FRPN

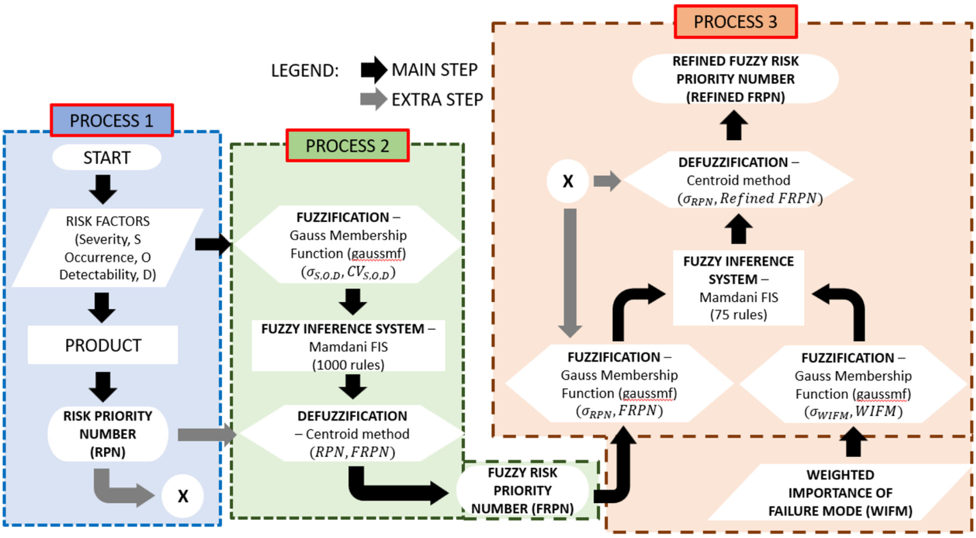


Fig. 13. Risk-based Maintenance Methodology of the Current Study

3 Results and Discussion

3.1 The Failure Modes

Upon thorough system evaluation of the process flow diagram, there were found a total of 37 failure modes which included the mechanical components (FM1 to FM15), electrical components (FM16 to FM23), and auxiliary components (FM24 to FM37). Further, FM1 to FM5 is about the submersible pumps, FM6 to FM13 is about the submersible aeration blowers, FM14 to FM15 is about the chlorinator pump, FM16 to FM17 is about indicating and initiating circuits, FM18 to FM19 is about the electrical components of submersible pumps, FM20 to FM21 is about the electrical components of submersible aeration blower, FM22 to FM23 is about the electrical components of chlorinator pump, FM24 to FM35 are various auxiliary components found in the sewage treatment facility. Table 4 reveals the failure modes for the study, and their corresponding definition.

Table 4. Failure modes, and their definition.

Failure Mode No.	Definition	Failure Mode No.	Definition
FM1	Clogging of submersible pump suctions	**FM20**	Overheating of submersible aeration blower electric motors
FM2	Wearing of submersible pump mechanical seals	**FM21**	Short circuit in the submersible aeration blower electrical lines
FM3	Wearing of submersible pump bearings	**FM22**	Malfunctioning of the chlorinator pump electric motor
FM4	Wearing of submersible pump impellers	**FM23**	Short circuit in the chlorinator pump electrical line
FM5	Wearing of submersible pump shafts	**FM24**	Wearing of bar screen
FM6	Malfunctioning of submersible aeration blower suction silencer	**FM25**	Wearing of wastewater piping connectors (flange or coupling)
FM7	Malfunctioning of submersible aeration discharge silencers	**FM26**	Loosen wastewater piping suppor
FM8	Wearing of submersible aeration blower shafts or rotors	**FM27**	Wearing of wastewater piping control valves
FM9	Wearing of submersible aeration blower bearings	**FM28**	Wearing of wastewater piping check valves
FM10	Wearing of submersible aeration blower mechanical seals	**FM29**	Malfunctioning of wastewater piping effluent flow meter
FM11	Wearing of submersible aeration blower flexible connectors	**FM30**	Wearing of air pipeline connectors (flange/coupling)
FM12	Malfunctioning of submersible aeration blower pressure gauge	**FM31**	Wearing of air pipeline check valves
FM13	Wearing of submersible aeration blower check valves	**FM32**	Loosen air pipeline supports
FM14	Wearing of submersible aeration blower safety valves	**FM33**	Wearing of air pipeline control valves
FM15	Malfunctioning of the chlorinator pump	**FM34**	Wearing of air pipeline fine bubble diffusers
FM16	Short circuit in the motor control center	**FM35**	Wearing of air pipeline coarse bubble diffusers

FM17	Malfunctioning of float switches	**FM36**	Formation of sewer gas
FM18	Overheating of submersible pum electric motors	**FM37**	Formation of scale
FM19	Short circuit in the submersible pump electrical lines		

3.2 Consensus Values for Chamber Relative Importance and Risk Factors of the Failure Modes

3.2.1 Chamber Relative Importance and Weighted Importance of the Failure Modes

Based on the responses, it was found that LS < EQT < CCC < ASD < SBR is the order of importance having the weighted averages 16.6, 18, 18.47, 23.4, and 28.53, respectively. Fig. 14 reflects the frequency distribution for Chamber relative importance.

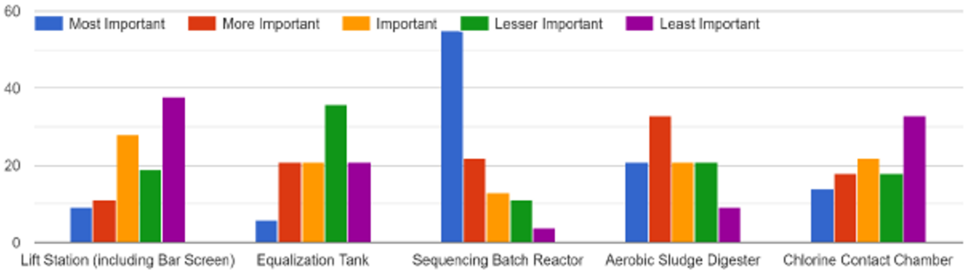


Fig. 14. Chamber Relative Importance of SBR-Type STF.

Upon identifying each chamber's relative importance, each failure mode's weighted importance was evaluated depending on the number of affected chambers. Failure modes that exist in most chambers obtained higher weighted importance. On the other hand, failure modes that only exist on one (1) to two (2) chambers obtained lower weighted importance. The weighing of failure modes' importance would increase the precision of failure modes that are more relevant and should be prioritized in maintenance decision-making. Its impact was reflected in the Refined FRPN computation. Fig. 15 reveals the weighted importance of the failure modes.

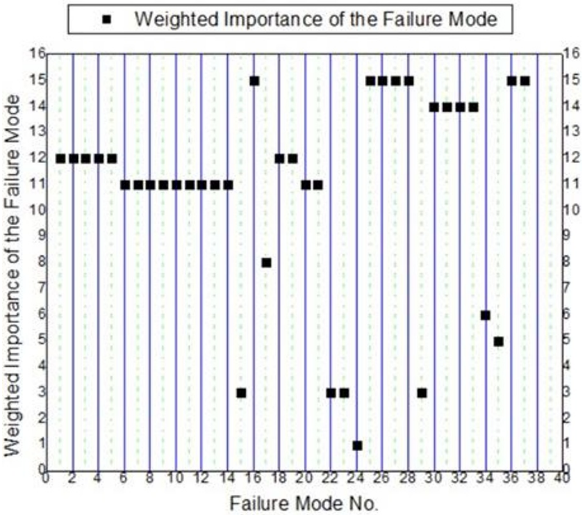


Fig. 15. Weighted Importance of the Failure Mode

3.2.2 Consensus Values for Risk Factors of the Failure Modes

The consensus values for risk factors were the central tendencies median or mode, whichever was fitter to represent the population. By default, the median shall be used but in other cases like in the Fig. 16, the mode shall prevail. Fig. 17 shows the plot of the consensus values for the risk factors for each failure mode.

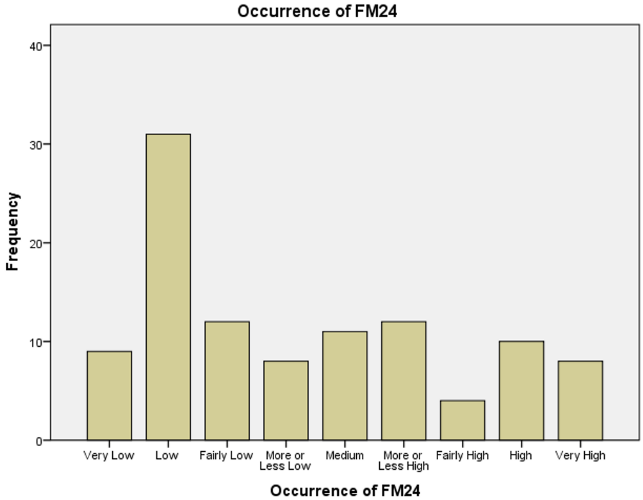


Fig. 16. Sample case when mode should be used as consensus value

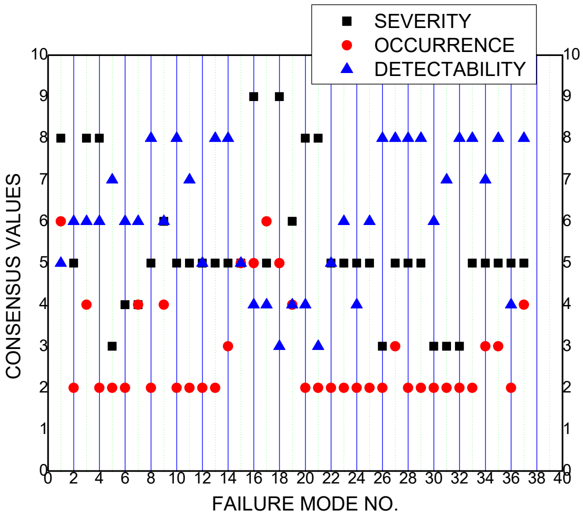


Fig. 17. Consensus Values of Risk Factors of the Failure Modes

3.3 Priority Numbers

This section focuses on the priority numbers obtained using the RBM methodology. Each main process has an output of a priority number where the iteration follows the RPN, FRPN, and Refined FRPN, respectively. Fig. 18 reveals the priority numbers: RPN, FRPN, and Refined FRPN.

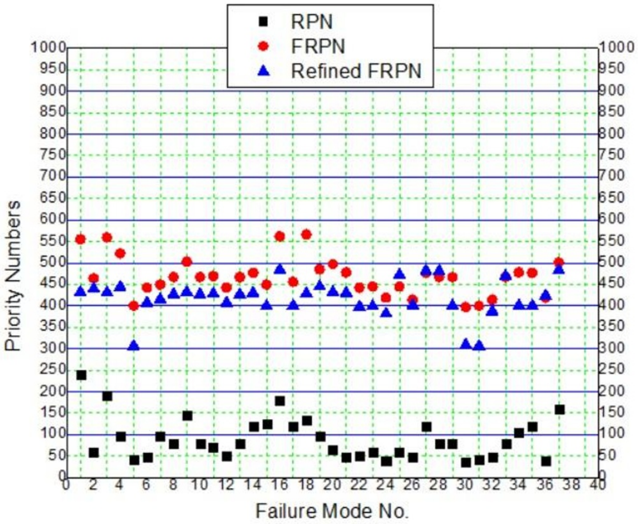


Fig. 18. Failure modes and their corresponding priority numbers

3.3.1 Risk Priority Number (RPN)

Based on the data, eight (8) sets of failure modes that are irrelevant to each other obtained the same values. FM24 and FM36 both obtained an RPN of 40 where the functionality of the former does not affect the latter. The immediate effect of the former is on the LS alone while the latter could manifest on EQT or SBR when the aeration blowers malfunctioned.

Also, we have FM5 and FM31 which both obtained an RPN of 42. FM5 relates to the pump, while FM31 relates aeration blower. Hence, they are irrelevant to each other.

The FM6, FM21, FM26, and FM32 shared the RPN of 48. FM6 is about the suction silencer malfunctioning which does not concern FM26 and FM32 but could be of concern to FM21 as any debris that enters the suction silencer may block the airways of the aeration blower which will eventually lead to electrical failure. On the other hand, FM26 and FM32 are relevant to each other as they are both support for the fluid piping.

Other failure modes that obtained the same RPN values that are not relevant to one another are FMs 12 and 22 having a value of 50. The former deals with the aeration blower while the other deals with the chlorinator pump.

At an RPN value of 60, FM2 and 25 are relevant to each other as the former deals with the mechanical seal of the submersible pump which may cause electrical concerns, while the latter deals with wastewater pipe connection. However, FM23 shared the same RPN value which deals with the chlorinator pump electrical line. The power lines of the submersible pump and the chlorinator pump is not connected.

Multiple failure modes FM8, FM10, FM13 and FM33 are relevant to each other as the occurrence of one could prompt the others. However, they share same RPN value of 80 with FM28, and FM29 which are not related to any failure in the aeration blower.

Sharing the RPN value of 96 are FM4, and FM19 which are relevant to each other as the occurrence of FM4 may prompt FM19. However, they share the same RPN with FM7 which is not related to the submersible pump.

The FMs 14 & 35 obtained an RPN of 120 which are relevant to each other as the occurrence of FM14 could affect FM35 since they share the same air pipelines. However, they share the same RPN with FM27 which is not related to the air pipelines.

Indeed, considering the RPN value could not yield a credible result to be used for maintenance decision making. The data justified the weakness of using the traditional RPN.

3.3.2 Fuzzy Risk Priority Number (FRPN)

Based on the data, six (6) sets of failure modes that are irrelevant to each other obtained the same values. FM5 and FM31 both obtained an FRPN of 400 where the functionality of the former does not affect the latter as FM5 concerned with a moving part of the pump while FM31 concerns the air pipelines. Hence, irrelevant to each other.

Just like in the computation of RPN, FM 24 and FM36 obtained the same FRPN value at 419. To reiterate, the effect of FM24 is at LS alone while the effect of FM36 could occur at EQT or SBR.

In the RPN computation, FM12 and FM22 obtained the same value at 50. On the other hand, their value concerning the FRPN was 442. They are irrelevant to each other as FM12 concerns a component in the aeration blower while FM22 concerns the chlorinator pump electrical component. Moreover, in the FRPN computation, they share value with FM6. The FM6 and FM12 are relevant to each other as they are passed through by air during the aeration process.

Other failure modes that are irrelevant to each other are FM23 and FM25 sharing the same FRPN value of 445. FM23 is under the failure modes for electrical components while FM25 lies at the failure modes for auxiliary components.

FM7 and FM15 obtained an FRPN of 449. However, they are irrelevant to each other despite being included together on the mechanical components as FM7 deals with a component of the aeration blower while the other concerns the chlorinator pump.

Six (6) FMs that flocked at FPRN value of 467 are FM8, FM10, FM13, FM28, FM29, and FM33. Four (4) FMs among the six (6) are relevant in the aeration blower and these are FM8, FM10, FM13, and FM33 while the remaining two (2) are relevant in the wastewater pipelines and these are FM28 and FM29. Nonetheless, the four (4) FMs are not related to the remaining two (2).

With the FRPN value of 477, FM14 is related to FM35 as the air processed by the aeration blower passes on both components. However, they share the same FRPN value with FM27 which concerns the control valves of wastewater piping. Although FM35 is not related to FM27, FM14 does have relevance with FM27 as they are both concerned with valves.

Based on the results, it is also found that two (2) sets of failure modes with the same FRPN value are relevant to each other. FM26 and FM32 obtained an FRPN value of 414, and concerning their functionality, having the same FRPN makes sense as both concern fluid piping.

The other is FM21 and FM34 having FRPN values at 478, FM34 deals with the functional failure of the fine bubble diffusers while FM21 deals with the functionality of the aeration blower in the electrical context. Though FM21 falls under the electrical component, and FM34 falls under the auxiliary component, both are relevant to the aeration process.

In summary, FRPN reduces the number of failure modes with the same priority number but irrelevant to each other. The weakness of the traditional RPN was somehow overcome by utilizing the FRPN. The maintenance decision-making using the FRPN values could provide a more sensible maintenance inspection and scheduling, but could also be further improved using the Refined FRPN.

In the context of the sewage treatment facility, the FRPN treats the chambers and failure modes equally. This could be an ideal case if the treatment is on a per-chamber basis. However, in reality, each chamber functions distinctly than the other. Hence, one is more important or less important than the other. The relative importance of each chamber is necessary to ensure that a particular chamber receives the treatment it requires to align the priority number based on the risk it should have. With that, failure modes situated in numerous chambers should have greater priority than those that are only present in one (1) or two (2) chambers. Hence, to have a more apt categorization and prioritization of risk, further processing is necessary.

3.3.3 Refined Fuzzy Risk Priority Number (Refined FRPN)

Based on the data, three (3) sets of failure modes that are irrelevant to each other obtained the same values. FM5 and FM31 both obtained a Refined FRPN value of 306. FM5 concerns the shaft of the submersible pump while FM31 concerns the check valve of the air pipelines, and therefore, are irrelevant to each other.

Four (4) FMs obtained a Refined FRPN of 400 and these are FM17, FM29, FM34, and FM35. FMs 34 and 35 are relevant to each other as they are both essential in the aeration process. However, they shared values with non-related failures FM17 which is concerned with the functionality of the float switches which affects the transfer of wastewater from one chamber to another, and FM29 which is an auxiliary component in measuring the amount of effluent being discharged to the environment.

At the Refined FRPN of 432, the FMs 1, 9, and 20 shared the same value. FM9 is relevant to FM20 as the occurrence and persistence of FM9 could result to FM20. However, FM1 is concerned with the submersible pump while the two (2) is concerned with the aeration blower.

The data also reveals four (4) sets of FMs that are relevant to each other. At a Refined FRPN value of 399, the FM23 obtained the same value as FM15. The occurrence of FM15 could prompt FM23, and vice versa.

At Refined FRPN of 407, the air from the aeration blowers flows on both suction silencer and pressure gauges making FM6 and FM12 relevant to each other.

FM8, FM10, and FM13 which concern the mechanical components, aeration blower, obtained a Refined FRPN of 427.

At Refined FRPN of 430, FM14 and FM21 shared the same value. FM14 is related to FM21 as the occurrence of FM14 could prompt FM21 by means of electrical tripping.

Based on the results, considering the FRPN values alone would be less effective in prioritizing risks in the context of SBR-type STF compared to Refined FRPN. Incorporating the weighted importance of each failure mode by identifying the relative importance of each chamber determines the relevant failure modes that could aid the maintenance decision-making.

Notable improvements in utilizing the Refined FRPN are the following: a) the failure modes for submersible pumps' electrical components (FM18-FM19) obtained values within the range of its mechanical counterparts (FM1-FM14) that is from 429 to 445 compared to FRPN with values ranging from 464 to 566, b) the failure modes for submersible aeration blowers' electrical components (FM20-FM21) obtained values within the range of its mechanical counterparts (FM6-FM14) that is from 407 to 432 compared to FRPN with values ranging from 442 to 503, c) the failure modes for auxiliary components (FM23-FM27) obtained values that are more sporadic ranging from 306 to 482 compared to FRPN with values ranging from 397 to 501. With this, utilizing the Refined FRPN is more apt compared to FRPN in maintenance decision-making in the context of SBR-type STF.

4 Conclusion

Considering the failure modes that obtained Refined FRPN values close to each other concerning their functionality and relevance, hence the RBM methodology is successful in devising an approach suitable for SBR-type STF for high-rise residential properties. Utilizing the results of this study in the maintenance aspect of operation could address the issue of failing effluent parameters to the establishments having an ineffective maintenance approach. Considering that residential properties obtain most of their budget through condominium dues, effective allocation is necessary to prevent equipment breakdown. Incorporating the results of this study could improve the resource allocation by effectively deploying the number of personnel required and determining the amount of time it would take to accomplish the tasks relating to the failure modes. In macro-scale, the application of the RBM methodology to the maintenance of STF ensures the compliance with the regulatory bodies and consequently reduces the number of establishments that operate with violations. Finally, this paper could only address the maintenance aspect of the bigger issue that is discharging of mistreated effluent into the environment. Future works could contribute by tackling the other facets of STF operation using equivalent methodology.

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