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Sustainability Assessment of a Municipal Sewage Treatment Plant using a Single Green Performance Indicator

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A Municipal Sewage Treatment Plant (MSTP) involves multiple processes for treating wastewater. In a MSTP, there are resources consumed, emissions as well as effluent discharged that could potentially cause environmental problems. There has bezen much research about environmental impact of a MSTP such as the MSTP carbon footprint, MSTP energy consumption and MSTP emission discharge. Although these studies have contributed towards reduction of environmental impact of a MSTP, so far, there has not been any study done to quantify the overall green performance of an MSTP. This paper extends the Green Index (GI) tool for the assessment of an MSTP environment. This study is focused on investigating the green performance of two types of MSTP, namely the Ludzack-Ettinger process and Bardenpho process. The conventional process is used as the benchmark for the purpose of comparison. The GI development for a MSTP involves two stages. The first stage involves formulation of a weighting scheme by applying factor analysis on the green elements data of the MSTP. This is followed by formulation of the GI using stock market composite index. The GI allows the use of a single index to be used to quantitatively assess the overall green performance, and the actual measure of the overall greenness of the MSTP facility. A single quantitative index to substitute multiple green elements would help organisations to objectively compare and select the type of MSTP process that is greener, promotes cleaner production, and has less adverse impact towards the environment. GI could help organisations to quantitatively and effectively monitor and analyse the actual green performance of a process in a retrofit or a conservation program. Result shows that GI would help organisation to choose which process would have less environmental impact. The GI graph accommodates facility manager with a figurative tool to visualise on the performance of MSTP either for retrofit or conservation programmed.

1. Introduction

Municipal Sewage Treatment Plant (MSTP) is a system to treat wastewater into clean water. The processed water is not for human consumption, but to be used for other activities such as for agricultural or to be discharge into the river. Before the wastewater can be disposed to the environment, the processed water must meet the standards and regulation that has been outlined by the respective country's authorities (Ancione et al., 2014). MSTP is constructed in urban area which have a rapid development and produce large volume of untreated sewage (Singh et al., 2016), such as university campus, township and palm oil mill. In Malaysia, a sewage treatment plant is mandatory to treat wastewater in urban area and township through Environment Quality Act 1974, Environmental Quality (Sewage) Regulations 2009 and Environmental Quality (Industrial Effluent) Regulations 2009 (Farid et al., 2016). According to Gebicki et al., (2016), the typical MSTP process involve as follows:

1. Separation of solids and floating particles by mechanical treatment.
2. Decomposition by biological treatment under aerobic condition.

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3. Nutrient removal by biological treatment.
4. Water purification by filtration, osmosis and coagulation.

Throughout the process, there are resources consumed, emissions as well as effluent discharged that could potentially cause environmental problems. Many researchers investigate on how MSTP affects the environment negatively. Chai et al. (2015) mentioned that sewage treatment plant in China consume about 0.4 % of the total China electricity consumption and becomes one of the cause for global warming. Singh et al. (2016) highlighted that in India, a small-scale sewage treatment plant consumes energy twelve times more than a large-scale sewage treatment plant. Li et al. (2016) also found out that a large scale MSTP consume less electricity consumption compare with small scale MSTP and this might be due to the adopted technology in MSTP processes, Masuda et al. (2015) in his study mentioned that MSTP main source of greenhouse gas (GHGs) contribution is from electricity consumption. Apart from electricity consumption and GHG emission concern, previous research also highlighted the environment degradation due to effluent discharge of MSTP. Tehrani et al. (2016) mentioned that effluent discharge must be managed efficiently or it would be the source of surface water contamination.
Due to the fact that MTSP operation and discharge contribute to environment degradation, many studies have been done to assess MSTP performance. Most popular tool to asses MSTP performance is the Life Cycle Assessment (LCA) method. Alfonsín et al. (2015) conduct LCA to assess environmental impact of odour abatement technologies in wastewater treatment plant. Meneses-Jácome et al. (2016) use LCA to assess wastewater environmental impact as the criteria for MSTP performance. Lorenzo-Toja et al. (2016) mentioned that LCA method is a thorough environmental assessment to evaluate MSTP performance in Spain. Although these studies have contributed towards reduction of environmental impact of a MSTP, so far, there has not been any study done to quantify the overall green performance of an MSTP. This study aims to extend the Green Index (GI) tool by Mustapha et al. (2016) for the assessment of an MSTP environment. This study is focused on investigating the green performance of two types of MSTP, namely the Ludzack-Ettinger process and Bardenpho process. The conventional process is used as the benchmark for comparison purposes. The GI allows the use of a single index to be used to quantitatively assess the overall green performance, and the actual measure of the overall greenness of the MSTP facility. This method would provide a standard and consistent assessment protocols. With only a single quantitative index to substitute multiple green elements, the GI would help organisations to objectively compare and select the type of MSTP process that is greener, promotes cleaner production, and has less adverse impact towards the environment.

2. Methodology

The GI development for a MSTP involves two stages. The first stage involves formulation of a weighting scheme by applying factor analysis to green elements data of the MSTP. This is followed by formulation of the GI using stock market composite index. The weighting scheme is part of composite index calculation to formulate GI.

2.1 Development of weighting scheme

Weighting scheme is a set of numbers that signify the importance of variables. The weighting scheme is developed by adopting factor analysis method. Factor analysis is a method that is capable to extract the unobserved factor between multiple variable. The factor analysis equation model is expressed as follows:

$$C = AF + E \quad (1)$$

This equation is represented in matrices, where C is the matrix of observed correlation coefficient, A is the matrix of unobserved variables, F is the matrix of correlation between all observed variables and E is the unique variance. The weighing scheme is derived from factor loading of the Factor analysis by determining the eigenvalue and eigenvector of matrix F using the following equation:

$$Av = \lambda v \quad (2)$$

Where λ represent the eigenvalue and v represent the eigenvector of matrix A. Microsoft Excel program with XLSTAT was used to compute all the statistical and mathematical calculation in this study.

2.2 Formulation of Green Index

GI is developed by adopting the stock composite index formulation. The common equation used in stock composite index is the capitalisation-weighted index and expressed as follows:

Capitalisation weighted index = $\frac{\sum p_t q_t}{\sum p_o q_o}$ x 100 (3)

Where p_o is the previous stock price, q_o is the previous stock holding quantity, p_t is the present stock price and q_t is the present stock holding quantity. All of the mentioned variables are the independent variables while composite index is the dependant variable. Note that, this equation is a capitalisation-weighted index, where any changes in independent variables would change the composite index value. To develop the green index, all independent variables in Eq(3) will be represented by green elements. In this study, the green elements (p_o and p_t) are water consumption (WC), electricity consumption (EC), carbon dioxide emission (CO_2), air consumption (AC), nitrogen emission (N_2), nitrate concentration (NO_3), Biochemical Oxygen Demand concentration (BOD_5) and Chemical Oxygen Demand concentration (COD). p_o and p_t are represented by green elements due to the fact that in stock market the price fluctuate due to trading activity which similar concept to a process where green elements consumption or emission discharge fluctuate due to process activity. q_o and q_t signify the importance of the stock within the composite index. q_o and q_t will be represented by weighting scheme as mentioned in section 2.1. The GI equation express as follows:

Green Index = $\frac{\sum I_t w_o}{\sum I_o w_o}$ (4)

Where I_o is the base period value of green elements, I_t is the present value of green elements and w_o is the base period weighting scheme. Eq(4) shows that the green index is the summation of green elements multiply with weighting scheme. The weighting scheme considers only base period value due to the assumption that the weighting of the green elements which based on process activities does not change for the given time period. A positive GI value indicates an increase in environmental degradation, and vice versa.

3. A case study on green performance of an MSTP process

The focus is on the modelling and retrofit of a MSTP. Three case models were used. First model, as illustrated in Figure 1, is a base model which represents the typical MSTP without nitrogen removal. Second model, as shown in Figure 2, is the modified model name as Ludzack-Ettinger process which includes the nitrogen removal. Third model was a model named as Bardenpho process which also includes nitrogen removal, as shown in Figure 3. The first model was used as the base model to compare the GI between Ludzack-Ettinger process and Bardenpho process. All of the case model has the same input influent amount which is 1,892.74 m^3/h and the output at every step was generated using SuperPro Designer v8.5. The schematic for the three case models are as shown in Figures 1 to 3.

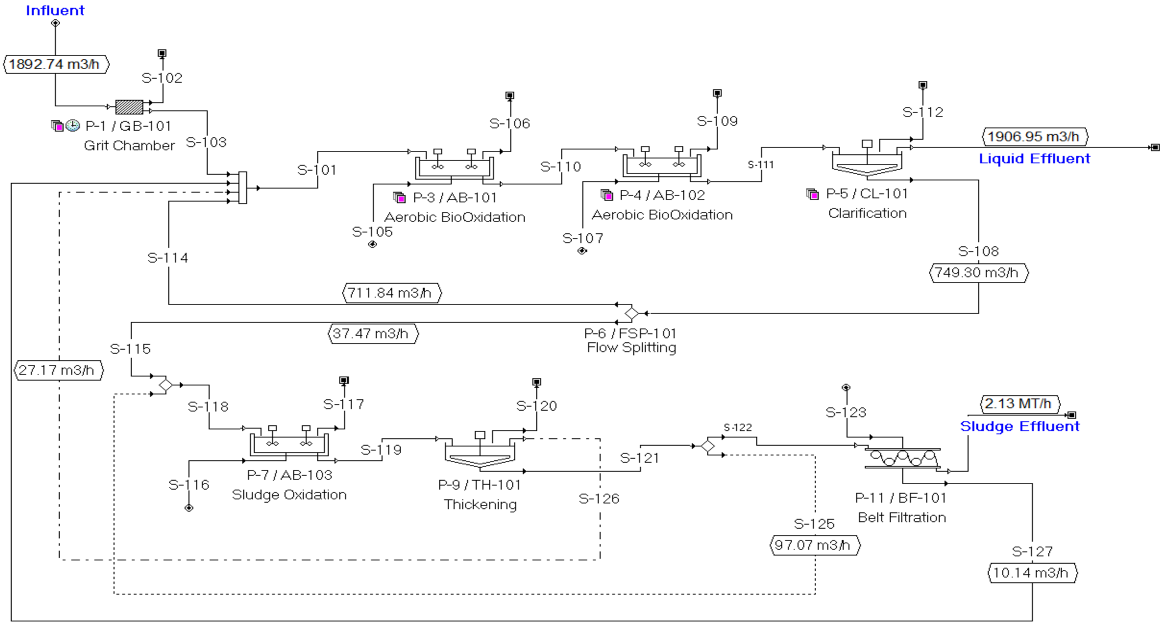

Figure 1: MSTP schematic diagram – base case process

4. Results and Discussion

4.1 Determination of the weighting scheme

The base case model was simulated using Superpro Designer v8.5 and the output data is as shown in Table 1. The data was grouped into primary treatment, liquid effluent, secondary treatment, final treatment and sludge effluent. It was grouped in this manner to identify at which process contribute the most towards environmental degradation. As mentioned earlier in Section 2.2, the green element chosen for this case study are WC, EC, CO_2, AC, N_2, NO_3, BOD_5, COD. The selected green elements would be different depending on the process and function of the facility. The data from Table 1 was factor analysed following Eq(1) and (2) and yielded two unobserved factor named as F1 and F2 as shown in Table 2.

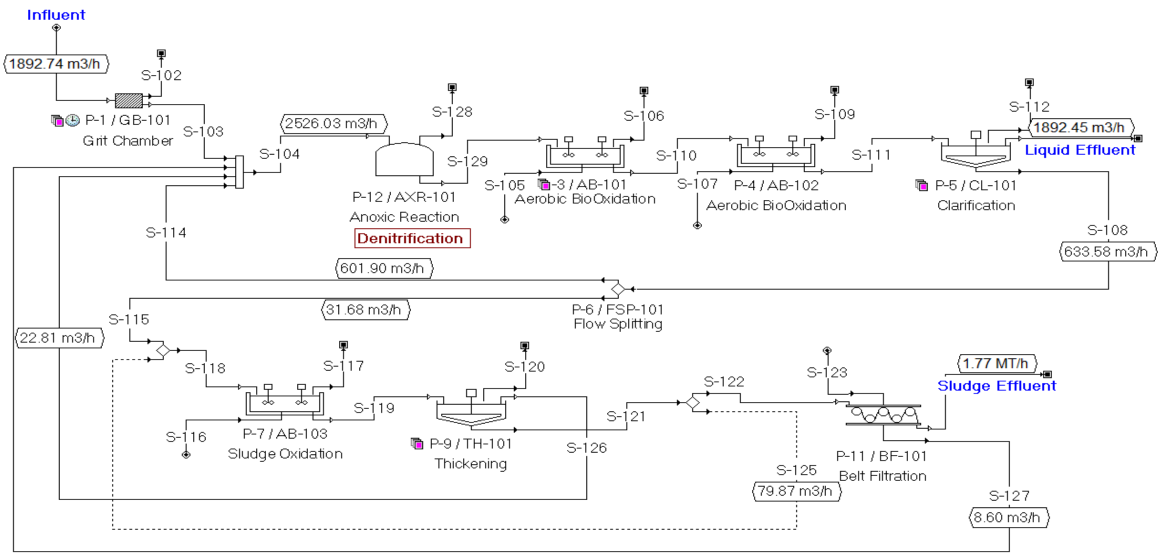

Figure 2: MSTP schematic diagram – Ludzack Ettinger process

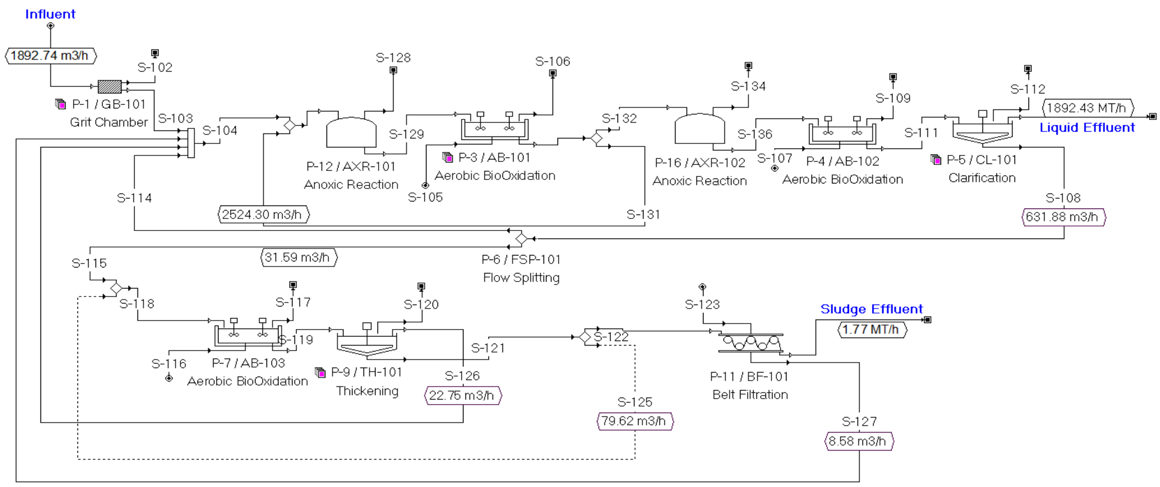

Figure 3: MSTP schematic diagram – Bardenpho process

Table 2 shows that there are two unobserved factor that significantly influence the green elements of the MSTP process. The influence or correlation strength between unobserved factor and green elements is stated in term of percentage where F1 = 59.9 % and F2 = 30.10 %. The percentage was calculated by dividing the eigenvalues by the number of independent variable in Table 2. There are two unobserved factor for this case study, only one unobserved factor will be used as weighting scheme. Unobserved variable F1 will be chosen as it has higher correlation strength compared with F2. Within the unobserved factor F1, there are numbers assign to each green element. These numbers are the factor loading and the weighting scheme for the green elements. This number represent the w_o value as mentioned in Eq(2) and will be used to calculate the GI.

4.2 Green Index development for comparison of MSTP green performance

In Section 4.1, the weighting scheme development has been discussed. This section compares the Ludzack-Ettinger process and Bardenpho process performance using Green Index methodology. SuperPro Designer v8.5 was used to simulate data for the Ludzack-Ettinger process and Bardenpho process. The simulated data was factor analysed using Eq(1) and (2) and the GI was calculated using Eq(4). The GI trend result is as shown in Figure 4.

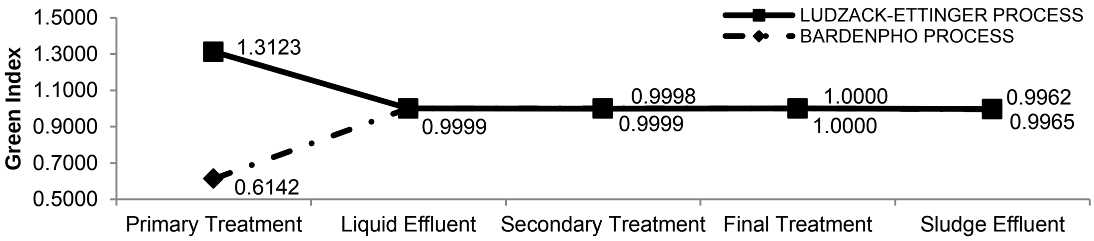

Figure 4: Green Index trend

Figure 4 shows a significant difference in greenness performance of these two processes specifically at Primary treatment. At primary treatment, Ludzack-Ettinger has a higher GI compared to Bardenpho process. Although development of GI is similar to stock market composite index methodology, a positive stock market composite index value is desired which mean a profit generated from trading session. In contrary with GI, an increment in GI means an increase in environment degradation. Ludzack-Ettinger process has a higher GI at primary treatment and small differences at secondary treatment and sludge effluent compared with Bardenpho process. Ludzack-Ettinger process gives more impact towards environment degradation compared with Bardenpho process. This can be explained by looking at the steps involved in primary treatment. Ludzack-Ettinger process has one anoxic reaction process compared with Bardenpho process that has two steps of anoxic reaction. Although with two anoxic reaction would consumed more electricity consumption in Bardenpho process, the Nitrogen gas emission amount is smaller compared to Ludzack-Ettinger process., GI value for Ludzack-Ettinger process is higher compared to Bardenpho process although Bardenpho process consumed more electricity. Using GI methodology, it is easy for organisation to choose which process has less impact towards environment degradation and the trend allows facility manager to identify at which process need immediate attention and guide them to enhance the process performance.

Table 1: Green elements data

	WC (t/h)	EC (kWh/h)	CO_2 (kg/h)	AC (t/h)	N_2 (t/h)	NO_3 (mg/L)	BOD5 (mg/L)	COD (mg/L)
Base Case Process								
Primary Treatment	0	7.08	309.2	6.01	4.61	0	0	0
Liquid Effluent	1,891.26	0	2.02	0	0	8.8	22.82	41.89
Secondary Treatment	0	2.06	64.68	1.56	1.19	0	0	0
Final Treatment	1.50	0	0	0	0	0	0	0
Sludge Effluent	1.81	0	0.04	0	0	79.54	82,903.52	152,610.7
Ludzack-Ettinger Process								
Primary Treatment	0	28.33	300.19	4.51	9.52	0	0	0
Liquid Effluent	1,891.08	0	2.67	0	0	3.64	22.77	41.64
Secondary Treatment	0	2.06	64.17	1.56	1.19	0	0	0
Final Treatment	1.50	0	0	0	0	0	0	0
Sludge Effluent	1.77	0	0.04	0	0	77.77	82,693.44	152,009.9
Bardenpho Process								
Primary Treatment	0	41.08	296.24	3.61	2.78	0	0	0
Liquid Effluent	1,891.47	0	1.88	0	0	1.68	23.02	42.07
Secondary Treatment	0	2.06	64.47	1.56	1.19	0	0	0
Final Treatment	1.50	0	0	0	0	0	0	0
Sludge Effluent	1.79	0	0.04	0	0	77.37	82,664.58	151,956.9

Table 2: Weighting Scheme

	F1 (59.9 %)	F2 (30.10 %)		F1 (59.9 %)	F2 (30.10 %)
WC	-0.1679	-0.4447	N_2	0.9248	0.3807
EC	0.9287	0.3751	NO_3	-0.6923	0.7115
CO_2	0.9175	0.3865	BOD_5	-0.6588	0.7452
AC	0.9248	0.3807	COD	-0.6588	0.7452

5. Conclusion

GI as a single green performance indicator has been formulated for sustainability assessment of a Municipal Sewage Treatment Plant. First, the development of green element weighting scheme using factor analysis methodology. Second, the GI calculation using stock market composite index methodology. Three MSTP model design was used as case study, namely the Ludzack-Ettinger process, Bardenpho process and base case process as the benchmark for comparison purposes. Factor analysis was used as a basis to develop the weighting scheme. Factor analysis capability to extract the unobserved factor provide a standard and consistent assessment protocols and based on actual operating parameters. Weighting scheme also helps facility manager to identify which green elements has the large impact as an overall. Electricity consumption has the largest impact on green performance followed by Nitrogen emission and air consumption. This study also proposed GI as the green performance indicator for MSTP. GI value not only capable to indicate the green level of MSTP, it can also be plotted into graph., the graphical plot trend would help organisation to choose which MSTP model design has less environmental impact., it would help facility manager to pay more attention to process that has higher green index value either for retrofit or conservation programme.

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