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# A Mathematical Model for Techno-Economic Evaluation of Industrial Wastewater Sludge to Resources

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Wastewater has typically been regarded as an environmental problem and a source of health hazard. Converting wastewater into value-added products such as energy production, and various products recovery have become more attractive. Industrial wastewater sludge has become viable resource of many products such as fertilisers, soil conditioner and artificial aggregate or cement-like materials. The objective of this study is to develop a model to select the appropriate wastewater treatment units that could maximise resources recovery via a simple and cost effective technology while complying the environmental discharge limit. A superstructure of potential treatment technologies is proposed in this work. Ideal networks that consist of interconnections between few treatment technologies to remove contaminants and recover valuable products are obtained by maximising the Net Present Value (NPV) for the plant. The model recommends the connection between anaerobic digester (AD), sludge pump (SP) and bio solid utilisation (BS) to reduce the final concentration in the effluent and at the same time generate the maximum amount of bio solid (soil conditioner) for agricultural purposes. Results of the proposed network yields an optimal network selected by the model that gives a positive NPV of USD 4,035, 506.

## 1. Introduction

Industrial wastewater has been considered as a major source of environmental pollution due to its high amount of organic content and other contaminants such as heavy metals and chemicals. Industries such as food and beverage, cosmetics, pharmaceuticals, pulp and paper use organic substances in their processes and produce biological high-strength wastewater (Hamza et al., 2016). The state-of-the-art treatment of wastewater emphasises on the contaminants to be removed rather than resources to be recovered. Recent studies have focused on the development of sustainable wastewater treatment facilities where resources such as energy, water and materials can be cost-effectively recovered while reducing the environmental hazards (Criddle et al., 2010). There are many activities for resources recovery from wastewater that have been carried out with minimal changes to the wastewater treatment infrastructure. The energy harvesting from wastewater using a microbial electrolysis cells was conducted by Zeppilli et al. (2015). The resource recovery was carry out in an activated sludge systems with 125 % of energy recovery from the treatment. It is only suitable for a low strength wastewater. A lower operational cost to recover metals is often employed using an ion exchange method. Víctor-Ortega et al. (2016) performed the final purification of iron metal from catalyst in the secondary treatment of olive mill wastewater. The maximum iron adsorption capacity is successfully demonstrated with a strong acid cation exchange resin. Rehman et al. (2015) recovered heavy metals such as Cu, Ni and Pb by using the electrocoagulation process. Other than nutrients, resource such as organic carbon can be recovered from wastewater to produce biogas. Silvestre et al. (2015) reviewed the conversion of methane-rich biogas known as clean energy via anaerobic digestion process. Although the recovery of valuable resources seems promising in the market nowadays, the price of the technology needed for such resource recovery is still often viewed as exorbitant. van der Hoek et al. (2016) provides the planning and

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design methodology for deploying a sustainable technology in the context of resources recovery by considering the impact to economic, effectiveness of treatment technology and ability to comply with the environment limit. This paper develops a model that selects the appropriate wastewater treatment that could maximise resources recovery via a simple and cost-effective technology while complying with the environmental discharge limit. A superstructure model is used to account for various feasible connections between treatment technologies where it leads to mixed-integer nonlinear programs (MINLP). The MINLP refers to the existing of discrete variable and nonlinear function that presents in the constraints and the objective function. The problem is solved using General Algebraic Modelling System (GAMS, 2013). A popular technology and lower in operating cost which is anaerobic digestion and activated sludge (Tyagi and Lo, 2013) follows by few technologies for resources recovery is adapted in this study.

## 2. Materials and Method

### 2.1 Problem Statement

The synthesis problem can be stated as follows. Given

- A set of wastewater streams with fixed flow rates and concentration to be removed;
- A set of water sinks with known environmental limit concentration set by local authority;
- A set of treatment technology comprising primary treatment, resource extraction and product recovery with certain pollutant removal performance and cost.

The objective of the problem is to find the optimal network for resources recovery that maximises the net present value of the system. The binary variables represent the existing of interconnection between technologies while flows as well as treatment units are defined as continuous variables.
The set of wastewater streams are defined as variable i, I ∊ I with known flow rate and known contaminants k, k ∊ K such as Total Suspended Solids (TSS), Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD). On the other hand, the set of treatment units are defined as variable tu, tu ∊ TU that are amenable to form a various topologies as well as environmental limit constraints for the contaminants leaving the effluent.

### 2.2 Superstructure Representation

The data specification is represented by a superstructure that considers all possible connection within the network. The superstructure network is illustrated in Figure 1, consisting of a single wastewater stream and water sink, and four treatment technologies; 2 primary treatment technologies (anaerobic digester and activated sludge), 1 resource extraction (sludge pump) and 2 product recovery technologies (sludge drying bed and bio solid utilisation) and the model is being developed flexibly.

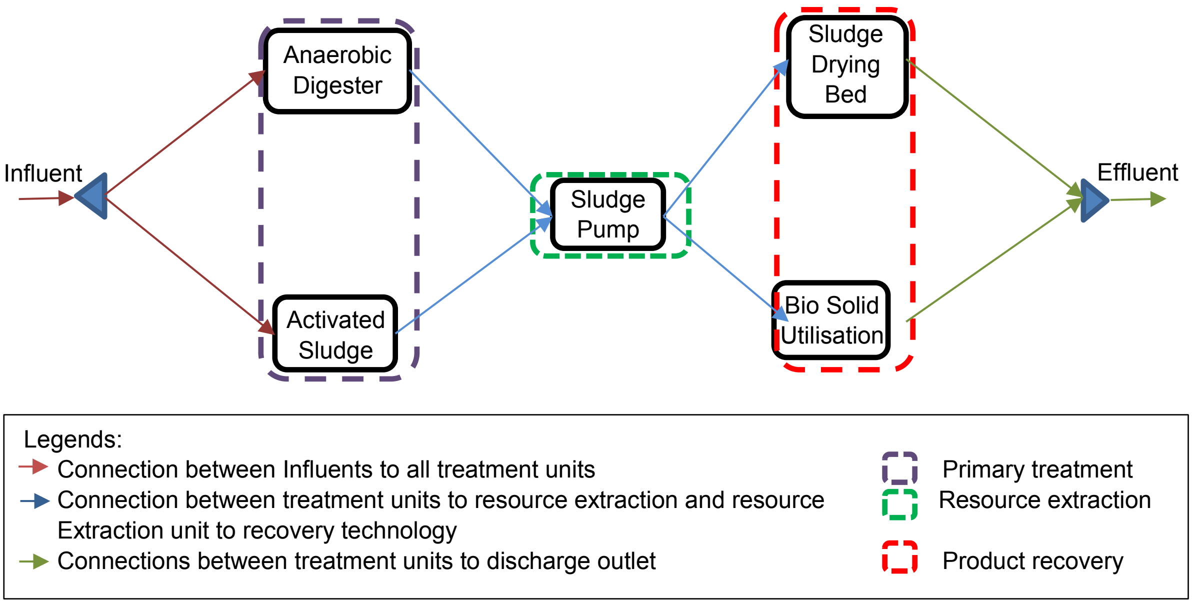


*Figure 1: Illustration of resources recovery possible pathway superstructure*

### 2.3 Mathematical Formulation

The objective function of the model is to maximise the Net Present Value (NPV) as given in Eq(1).

$$\max \mathrm{NPV} = -\mathrm{CAPEX} + \sum_{y=1}^{15} \frac{\mathrm{SALES} - \mathrm{OPEX}}{(1+\mathrm{dr})^{y}} \tag{1}$$

Where CAPEX, OPEX and SALES denote capital cost, operating cost and the revenue from the product sales, while dr refers to discounted rate equal to 5 %. The maximisation of the objective function is subject to constraints given by Eqs(2) to (11). The plant is assumed to have a service life, y, of 15 years.

The total flow rate from influent, i going into each treatment unit, TU, and from influent, i going into the final discharge, e is equal to the total influents flow rate at initial splitter.

$$\sum_{i} \mathrm{wwFtot}_{i} = \sum_{tu} \mathrm{wwF\_tu}_{i,tu} + \sum_{e} \mathrm{wwF\_fd}_{i,e} \qquad \forall i \tag{2}$$

To ensure the continuity of the operation, the flow entering and leaving the unit must be in steady state system. The total influent flow rates leaving the system are equal to final discharge flow rate from initial splitter and from each treatment units.

$$\sum_{i} \mathrm{wwFtot}_{i} = \sum_{i} \mathrm{wwF\_fd}_{i,e} + \sum_{tu} \mathrm{wwFtu\_fd}_{tu,e} \qquad \forall e \tag{3}$$

The total flow entering each treatment unit equals to the flow from influent to each treatment unit and from treatment units to another treatment unit.

$$\mathrm{Ftu}_{tu}^{in} = \sum_{i} \mathrm{wwF\_tu}_{i,tu} + \sum_{tu'} \mathrm{wwFtu\_tu'}_{tu,tu'} \qquad \forall tu \tag{4}$$

The mass load entering the treatment units is assigned with the following equation

$$\mathrm{Ctu\_in}_{tu,k} \text{ x } \mathrm{Ftu}_{tu}^{in} = \left(\sum_{i} \mathrm{wwF}_{\mathrm{tu}_{i,tu}} \text{ x } \mathrm{Ci}_{i,k}\right) + \left(\sum_{tu'} \mathrm{wwFtu}'_{\mathrm{tu}_{tu,tu'}} \text{ x } \mathrm{Ctu}_{tu,k}\right) \qquad \forall tu \quad \forall k \tag{5}$$

The removal of each contaminants is given with the removal efficiency at each treatment unit

$$\left(1 - \mathrm{RR}_{tu,k}\right) \text{ x } \left(\mathrm{Ctu\_in}_{tu,k} \text{ x } \mathrm{Ftu}_{tu}^{in}\right) = \left(\sum_{tu'} \mathrm{wwFtu\_tu'}_{tu,tu'} \text{ x } \mathrm{Ctu}_{tu,k}\right) + \left(\sum_{e} \mathrm{wwFtu\_fd}_{tu,e} + \mathrm{Ctu}_{tu,k}\right) \quad \forall tu, k \tag{6}$$

The final discharge of the wastewater treatment plant needs to comply with the environmental limit. The discharge limit is imposed on a given sink for contaminant k.

$$\mathrm{Ctu}_{tu.k} \leq \mathrm{Cl}_{k} \tag{7}$$

The ideal flow and concentration leaving each treatment unit is the solution to these set of treatment units and contaminants. The amount that was removed or recovered at the treatment unit is then calculated using the following equation.

$$\mathrm{Ctu\_recovered}_{tu,k} = \mathrm{Ctu\_in}_{tu,k} - \mathrm{Ctu}_{tu,k} \qquad \forall tu \ \forall k \tag{8}$$

The CAPEX, OPEX and sales to satisfy the objective function are given by the following equations. The cost function for capital and operating cost for each treatment unit (TU) is given by Metcalf and Eddy (2003) in Table 3.

$$\mathrm{capex} = \sum_{tu} \mathrm{Capex}_{tu} \text{ x } \mathrm{Btu}_{tu} \tag{9}$$

$$\mathrm{opex} = \sum_{tu} \mathrm{opex}_{tu} \text{ x H x } \mathrm{Btu}_{tu} \tag{10}$$

$$\mathrm{Sales}_{k} = \mathrm{Ctu\_recovered}_{tu,k} \qquad \forall k \ \forall tu \tag{11}$$

Where the total cost of the network is represented by CAPEX, $\mathrm{Btu}_{tu}$ binary variable defining the existence of the treatment unit within the optimal network, OPEX; the annual operating and maintenance cost; the recovered species at each treatment unit represented by $Ctu\_recovered_{tu,k}$ and H is annual operating hours. $V_{tu,k}$ is the value per unit of the recovered species from each unit per hour as given in Table 1 and the generation rate for the product recovered unit per ppm per year, RGenprod is the generation rate of the product from each recovered species where it is assumed to be 128 for Bio Solid and 0.77 for stockpile.

*Table 1: Value per unit of the recovered species, k from each treatment unit, tu per hour*

| Treatment unit/ Parameter | Anaerobic Digester (AD) | Activated Sludge (AS) | Sludge Pump (SP) | Bio Solid Utilisation (BS) | Drying Bed (DB) |
|---|---|---|---|---|---|
| COD | 0.00 | 108.99 | 0.00 | 0.00 | 0.00 |
| TSS | 108.99 | 0.00 | 0.00 | 150.00 | 70.00 |
| BOD | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

## 3. Case Study

A 100 t/h of effluent from an industrial effluent is considered as a synthesis for this case study with the contaminant concentration given in Table 2. The objective is to maximise the NPV given in Eq(1) while satisfying the environmental limit set by the Department of Environment Malaysia. These requirements include of complying the Standard B maximum concentration of 100 mg/L TSS, 40 mg/L BOD and 200 mg/L COD. The yearly operating hour for the plant is assumed to be 8,000 h/y. The cost summary for each technology is given in Table 3.
In order to accumulate a large sludge concentration at the resource recovery treatment units, the effluent from anaerobic digester or activated sludge must go through sludge pump before it can be transported to the bio solid utilisation and/or sludge drying bed.

*Table 2: Characteristic of the industrial wastewater, discharge limits and removal efficiencies for each TU (%).*

| Parameter | Inlet Concentration | $Cl_k$ | $RR_{tu,k}$ (AD) | $RR_{tu,k}$ (AS) | $RR_{tu,k}$ (SP) | $RR_{tu,k}$ (BS) | $RR_{tu,k}$ (DB) |
|---|---|---|---|---|---|---|---|
| TSS | 700 ppm | 100 ppm | 88.70 | 0 | 10 | 88.70 | 80 |
| COD | 1,500 ppm | 200 ppm | 91.40 | 0 | 99.99 | 81.40 | 0 |
| BOD | 2,000 ppm | 40 ppm | 99.99 | 89.14 | 98.00 | 96.00 | 0 |

*Table 3: Cost summary for each treatment technology (Metcalf and Eddy, 2003)*

| Treatment | Technology | CAPEX (USD) | OPEX (USD/y) | Included Elements |
|---|---|---|---|---|
| Primary Treatment | Anaerobic Digester (AD) | $-0.00002(Q)^2 + 21.28(Q) + 471,486$ | $0.67(Q) + 26,784$ | Include digestion tank, heat exchanger, gas mixing and collection equipment |
| Primary Treatment | Activated Sludge (AS) | $90(Q) + 612,777$ | $93(Q)^{0.834}$ | Include plug-flow aeration tank and aeration device |
| Resource Extraction | Sludge Pump (SP) | $-0.00005(Q) + 44.77(Q) + 323,702$ | 0 | |
| Product Recovery | Bio Solid Utilisation (BS) | $-0.00005(Q)^2 + 2.057(Q) + 76,790$ | $-0.000001(Q)^2 + 0.978(Q) + 22,031$ | Capex include transportation vehicle, sludge loading and unloading apparatus, concrete pad and storage facility. Opex include oil, gas, maintenance, labour and materials. No land cost involved. |
| Product Recovery | Sludge Drying Bed (DB) | $89(Q)^{0.854}$ | $-0.00002(Q)^2 + 2.57(Q) + 8003$ | Include sand beds, sludge inlets, underdrains, cell dividers, sludge piping, underdrain return and other structural elements |

### 3.1 Optimal Scenario Result

The optimal scenario was the one which the model maximise the investment NPV. Figure 2 represents the computed optimal flow sheet where the model is sending all influents flow to Anaerobic Digester (AD) although this technology has higher capital and operating cost compared to Activated Sludge (AS) technology. AD provides higher removal efficiency for all contaminants. TSS removal is especially paid attention by the model due to bio solid production where it is linearly related to the TSS removed. The model finds that the AD-SP-BS technology has the highest income with the least cost. The optimised flow sheet is shown in Table 4. All contaminants leaving the AD unit has achieved the maximum allowable limit for the final effluent therefore 100 % of the flow is directed towards the sludge pump followed by BS where TSS reduction occurs and bio solid is further recovered at bio solid utilisation with an income generated. A 0 % tolerance from the optimal solution provided by Baron solver is calculated.

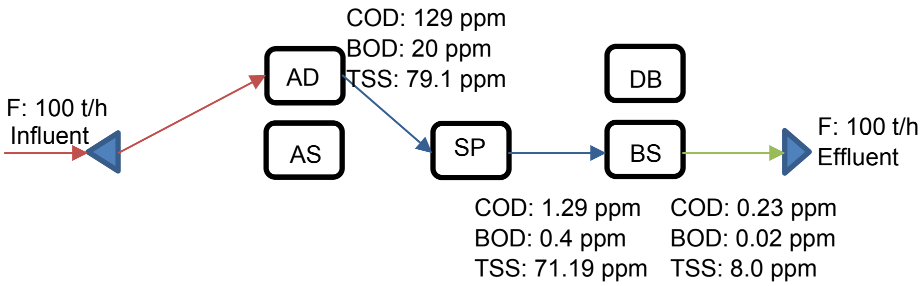


*Figure 2: The network for optimal scenario with flows and concentrations at TU outlet*

*Table 4: Results for optimal scenario*

| Parameter | Value |
|---|---|
| CAPEX (USD) | 20,903,170 |
| OPEX (USD/y) | 2,304,580 |
| Sales (USD/y) | 4,707,229 |
| Profit (USD/y) | 2,402,649 |
| NPV (USD) | 4,035,506 |

## 4. Conclusions

This paper has developed the possible combinations of different treatment technologies to produce a sludge resource recovery facility apart from wastewater treatment that normally discards sludge directly to landfill. The maximum recovery of resources can also reduce the environmental impact and generate income for the facility. The model was successfully applied using MINLP techniques. The solution however requires high computational power due to the bilinear terms exist in the model where it lead to a non-convex problem. There is opportunity to improve the proposed model by avoiding non convexity via linearisation of the nonlinear terms as to make the model more practical. There is also many other potential resources that can be recovered apart from sludge whereas for future research, an extension of optimal water and wastewater network (Sujak et al., 2015) considering cost-constraints in selecting the best water minimisation schemes (Sujak et al., 2017) integrating with resources recovery such as biogas, nutrients especially phosphorus and nitrogen, as well as biodiesel can be developed with various treatment technologies. A scenario-based analysis can also be applied in this model for performance and cost prognosis.

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**Nomenclature**

Sets

| | |
|---|---|
| E | Index for effluent (sink), E ∈ e |
| I | Index for inlet stream (source), I ∈ i |
| K | Index for contaminants, K ∈ {COD,TSS, BOD} |
| tu | Index for treatment units, tu ∈ {TU1,TU2…,TU} |

| | | |
|---|---|---|
| Positive Variables | | |
| NPV, CAPEX, OPEX, sales, profit | Financial Variable (self-explanatory) | [USD] |
| $\mathrm{Ci}_{\mathrm{i,k}}$ | Contaminant k in i | [ppm] |
| $\mathrm{Ctu\_in}_{\mathrm{tu,k}}$ | Concentration of contaminants in TU | [ppm] |
| $\mathrm{Ctu}_{\mathrm{tu,k}}$ | Contaminant k leaving TU | [ppm] |
| $\mathrm{Ctu\_recovered}_{\mathrm{tu,k}}$ | The amount of species recovered at each TU | [ppm] |
| $\mathrm{Ftu}_{\mathrm{tu}}^{\mathrm{in}}$ | Flow entering TU | [t/h] |
| $\mathrm{wwF\_fd}_{\mathrm{i,e}}$ | Flow between i to e | [t/h] |
| $\mathrm{wwF\_fd}_{\mathrm{tu,e}}$ | Flow between TU to e | [t/h] |
| $\mathrm{wwF\_tu}_{\mathrm{i,tu}}$ | Flow between i to TU | [t/h] |
| $\mathrm{wwFtu\_tu'}_{\mathrm{tu,tu'}}$ | Flow between TU to another TU' | [t/h] |
| $\mathrm{wwFtot}_{\mathrm{i}}$ | Total wastewater | [t/h] |
| Binary Variable | | |
| $\mathrm{Btu}_{\mathrm{tu}}$ | Existence of treatment unit | [1 or 0] |
| Parameter | | |
| $\mathrm{Cl}_{\mathrm{k}}$ | Discharge limit for contaminant k | [ppm] |
| H | Yearly operating hour | [h] |
| RGenprod | Regeneration rate of product | [Unit/ppm.y] |
| $\mathrm{RR}_{\mathrm{tu,k}}$ | Contaminant k removal ratio at each TU | [%] |
| $V_{tu,k}$ | value per unit of the recovered species from each unit per hour | [USD/h.unit] |
| y | Plant lifetime | [y] |

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