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# A Multiple Input Type Optimization Model Integrating Reuse and Disposal Options for a Wastewater Treatment Facility

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In the last few years, rapid industrial development coupled with globalization have brought about significant environmental impacts from both the industrial and urban settlements. Inadequate treatment and improper disposal of wastewater is a growing problem, causing health hazards and endangering nearby marine life. As such, it is more important to implement a sustainable strategy to reduce the harmful environmental impact of untreated wastewater. Optimizing wastewater treatment operations while tapping into the reuse potential of wastewater can improve the economic viability of a treatment plant. This study presents a mathematical model formulated to optimize the treatment process of wastewater. The model takes into account different input types in terms of quantity and quality, and various output or disposal options. Also, this study introduces the use of different input treatment options – mixed, parallel, and series – to better optimize according to the stakeholder's objectives. This integrated view of the system from input to output strengthens the model's capability to meet stakeholder requirements and optimize operations.

## 1. Introduction

The last decade has ushered significant global industrial development. It is estimated that an additional 2.5 billion people will be living in urban cities by the year 2050 (United Nations, 2014). The increasing world population coupled with the increasing concentration in urban cities have also led to the increase of waste generation annually, including municipal wastewater and sludge (Mateo-Sagasta et al., 2015). In some cities, wastewater and sludge are collected, treated, and beneficially reused. However, cities in developing countries are still unable to properly treat and dispose of the wastewater that growing urban cities generate. Disposal into the environment in water bodies without proper treatment causes pollution of surface and groundwater sources. Optimizing wastewater treatment operations while tapping into the reuse potential of wastewater improves the viability of the treatment process while supporting the lack of clean water supply in several regions.

Typically, wastewater treatment plants have several stakeholders with varying priorities (Belia et al., 2009). As stakeholders, the government imposes regulations for the necessary types of treatment permissible in an area and the required water quality levels allowed for disposal for each water body (Grady et al., 2011). Another consideration for the government is the economical upliftment of the nearby community. This can be attributed through the employment opportunities that the development and operations of a wastewater treatment facility offer (Boix et al., 2015).

There are various disposal and reuse options available for the wastewater treatment, which significantly affect both environmental and economic benefits of a wastewater treatment facility. However, there is a lack of integration in the current literature on wastewater regarding disposal and reuse options. As shown by Siy et al. (2016), considering both economic and environmental issues allow the model to optimize a more realistic facility setup. The environmental benefits of the optimization model can be better maximized with an integration as it matches the effluent water quality to the best suited disposal site or reuse option while taking into account the different disposal constraints set by local authorities. Disposal to water bodies that are not appropriate even after treatment can still cause environmental impact depending on the uses and composition of the water body. The treated water should be disposed to sites that would most fit its properties in order to maximize overall environmental benefit. Such integration will be demonstrated in this paper.

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## 2. Wastewater treatment network

The system begins with the input of wastewater from the municipal sewage system, continues as inputs pass through the wastewater treatment plant (WTP), and ends in the disposal or reuse of treated wastewater. The WTP initially consists of a set of available wastewater treatment processes. However, not all wastewater inputs are required to undergo each treatment process. Instead, a decision making network is introduced, where the choice of process steps is dependent on the water quality and the constraints of the model. Several surface and subsurface water bodies serve as possible disposal options from the environment of the WTP. Model constraints need to be taken into account, such as how the treated wastewater should meet a certain water quality level before they can be disposed to a certain water body. This is usually set by local government restriction, and it is also done to maximize the environmental benefits of the model. When soft constraints for disposal quality are not met, additional environmental costs will be incurred. Moreover, water reuse is also considered as a possible disposal option to accommodate regional demand that might present in some cases of application.

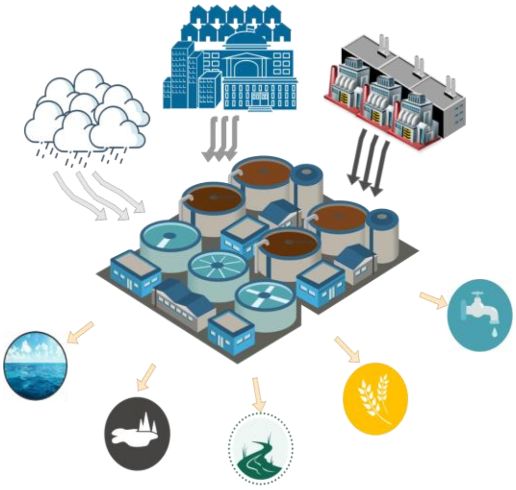

*Figure 1: System Network Diagram*

Wastewater input to the system is considered to be variable in terms of volume and quality. Water input is independent of each other and the quality is deterministic in nature. Water quality is one of the factors that will define what treatment processes the wastewater will undergo. Rainwater is also considered as an input to the system, but it serves as an agent to dilute wastewater in order to improve water quality. This is added to capture the realistic setting of most developed countries with rainwater pipes. Moreover, the system might choose to import freshwaters from freshwater sources when required in order to dilute the wastewater.

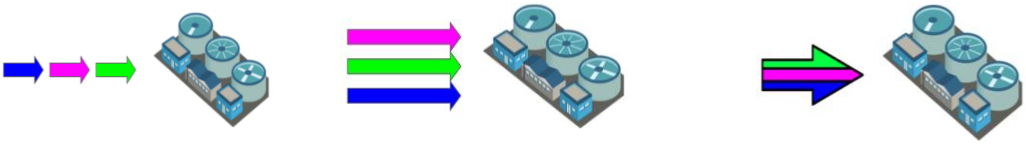

*Figure 2: Series, Parallel, and Mixed Input Treatment Options*

Mix, parallel, and series input treatment options are considered in the study. Each option has a specified setup cost and only one option can be used per period. In the mix input option, the different sources of wastewaters will mix together before they enter the WTP and they are treated as one quality level. Parallel means that wastewater inputs enter the WTP simultaneously without making contact with each other. In cases where inputs with different quality levels need to undergo the same treatment process, one batch would need to wait until the server (treatment process) becomes idle or it may undergo another viable treatment process and come back when that server is idle. On the other hand, when the series treatment option is being practiced, the different sources of wastewater will enter the WTP after each other and will be treated one by one.

The output demand of the system might affect the treatment processes, which will consequently influence the optimal values derived for the system. Output demand pertains to the reuse demand for the different applications of effluent water. Reuse applications are not limited to one desired quality considering that treated wastewater can be used for agricultural irrigation, recreational purposes, and potable water amongst others.

## 3. Model development

An optimization model is formulated by the researchers based on the system definition as discussed in the previous section. The notations for the indices, parameters and decision variables are presented in Table 1.

*Table 1: Indices, parameters and decision variables*

| Symbol | Definition |
|---|---|
| $i$ | Type of input in terms of quality to the system |
| $o$ | Output or disposal site available to the system |
| $p$ | Process for treatment within the treatment facility |
| $k$ | Time period in the planning horizon |
| $\boldsymbol{L_p}$ | Percentage loss of quantity of water from process *p* |
| $\boldsymbol{C_p}$ | Quantity capacity for treatment of process *p* for each infrastructure |
| $\boldsymbol{D_{ok}}$ | Total demand of the quantity of water to be disposed to output *o* during period *k* |
| $\boldsymbol{A_p}$ | Quality of water increased from undergoing process *p* |
| $\boldsymbol{AV_{ok}}$ | Quality requirement of water to be disposed to output *o* during period *k* |
| $\boldsymbol{PV_p}$ | Processing time for process *p* |
| $\boldsymbol{V_p}$ | Cost of process *p* for each quantity of water |
| $\boldsymbol{E_o}$ | Penalty cost of not meeting quantity demand for output *o* |
| $\boldsymbol{S_o}$ | Disposal cost for output *o* |
| $\boldsymbol{W_p}$ | Cost of initializing for process *p* |
| $\boldsymbol{H}$ | Holding cost per quantity per period |
| $\boldsymbol{G_p}$ | Construction cost of new infrastructure for period *p* |
| $\boldsymbol{TM}$ | Cost associated with time |
| $\boldsymbol{I_{ik}}$ | Quantity of input of water type *i* during period *k* |
| $\boldsymbol{F_{ik}}$ | Quantity of water type *i* untreated for holding from period *k* to the next period |
| $\boldsymbol{NV_{ik}}$ | Total quantity of water type *i* to be treated during period *k* |
| $\boldsymbol{N_{oik}}$ | Total quantity of water to be disposed in output *o* from water type *i* to be treated during period *k* |
| $\boldsymbol{Y_{poik}}$ | Binary variable where value is 1 when process *p* is undergone by water to be disposed in output *o* from water type *i* to be treated during period *k;* and value is 0 otherwise |
| $\boldsymbol{O_{ok}}$ | Total quantity of water to be disposed to output *o* during period *k* |
| $\boldsymbol{B_{pk}}$ | Number of infrastructures of process *p* available during period *k* |
| $\boldsymbol{R_{pk}}$ | Number of new infrastructures of process *p* to be built during period *k* |
| $\boldsymbol{Q_{ik}}$ | Quality of input of water type *i* during period *k* |
| $\boldsymbol{QF_{ik}}$ | Quality of water type *i* untreated for holding from period *k* to the next period |
| $\boldsymbol{U_{oik}}$ | Quality of water to be disposed in output *o* from water type *i* during period *k* |
| $\boldsymbol{T_{poik}}$ | Time ended for water after undergoing process *p* to be disposed in output *o* from water type *i* to be treated during period *k* |
| $\boldsymbol{M_{pk}}$ | Binary variable where value is 1 when process *p* is used during period *k;* and value is 0 otherwise |
| $\boldsymbol{FT_k}$ | Final time to process all water to be disposed during period *k* |

### 3.1 Constraints

The model formulated takes into consideration the quality and quantity of inputs and outputs, as well as the time and order constraints for the different processes. Constraints (1) to (6) establish the quantity constraints for the model. The amount of water inputted into the system while considering the water in inventory for this and the previous period would result into the total amount of water to be processed during this period (1). Eq(2) shows that the total amount of water processed is then equated to the water to be processed with the intent to be disposed in the different outlets available for the period. A percentage of the water treated is expected to be lost. Constraint (3) factors in the percentage of evaporated or extracted water and subtracts this from the water to be processed in order to determine how much water is to be disposed in each outlet.

$$I_{ik} + F_{i(k-1)} - F_{ik} = NV_{ik} \qquad \forall ik \tag{1}$$

$$\sum_{o} N_{oik} = NV_{ik} \qquad \forall ik \tag{2}$$

$$\sum_{i} N_{oik}(1 - \sum_{p} L_p Y_{poik}) = O_{ok} \qquad \forall ok \tag{3}$$

Eq(4) and (5) are concerned with the capacity of the processes in the treatment facility. The quantity of water that can be processed for each process is limited by the number of infrastructures available in that period for the process multiplied by the capacity of each infrastructure (4). The number of infrastructures available is defined by the number of infrastructures made in previous periods plus the amount maid in the current period (5). Spontaneous construction is assumed. The amount of water to be treated is then limited by the demand or capacity of the output (6).

$$\sum_{o}\sum_{i}(N_{oik}Y_{poik}) \leq B_{pk}C_{p} \qquad \forall pk \tag{4}$$

$$B_{pk} = B_{p(k-1)} + R_{pk} \qquad \forall pk \tag{5}$$

$$O_{ok} \leq D_{ok} \qquad \forall ok \tag{6}$$

Eq(7) to (9) are concerned with the equality constraints for the parallel and series input treatment type. The quality of the water type input to be treated for this period is equal to the weighted average of the quality of the water inputted this period and the quality of water left over from the previous periods (7). This quality is equal to the quality of the water left over by this period (8). In order to meet the quality requirements of each disposal outlet, each type of water would need to undergo a certain number of processes to improve its quality (9).

$$U_{oik} = {(Q_{ik}I_{ik}) + \left(QF_{i(k-1)}F_{i(k-1)}\right)}\Big/{I_{ik} + F_{i(k-1)}} \qquad \forall oik \tag{7}$$

$$QF_{ik} = U_{oik} \qquad \forall oik \tag{8}$$

$$U_{oik} + \sum_{p} A_{p}Y_{poik} \geq AV_{ok} \qquad \forall oik \tag{9}$$

In the mixed input treatment type, the quality of all the water to be treated for the period is taken from the weighted average of all the water inputs and all the holding water (10).

$$U_{oik} = \frac{\sum_{i}(Q_{ik}I_{ik}) + \sum_{i}\left(QF_{i(k-1)}F_{i(k-1)}\right)}{I_{ik} + F_{i(k-1)}} \qquad \forall oik \tag{10}$$

The next constraint pertains to the time or order for the processing of the different batches of water. In Eq(11), the time start of the processing of the water of each process should be after the time end of the previous process. For the series input processing type as shown in Eq(12), the input type can only be processed after the previous input has already used that process.

$$T_{poik} \geq T_{(p-1)oik}Y_{(p-1)oik} + PV_{p}Y_{poik} \qquad \forall poik \tag{11}$$

$$T_{poik} \geq T_{po(i-1)k}Y_{po(i-1)k} + PV_{p}Y_{poik} \qquad \forall poik \tag{12}$$

The final time for processing for each period k is then defined as the longest end time for all the processes and outputs (13). Constraint (14) defines whether the process was used in this period.

$$FT_{k} \geq T_{poik} \qquad \forall poik \tag{13}$$

$$M_{pk} \geq Y_{poik} \qquad \forall poik \tag{14}$$

### 3.2 Objective function

The objective of the wastewater treatment model is to minimize the costs incurred by the facility while meeting the demand and disposal constraints set. The stakeholder may opt to increase or decrease the time cost and unmet demand penalty cost according to operational objectives. The breakdown of the objective function is shown in equation (15). The breakdown of the cost components associated with the objective function of the model are illustrated in equations (16) to (21).

$$\begin{aligned} Min\ Z = {} & Processing\ Cost + Unmet\ Demand\ Penalty\ Cost + Disposal\ Cost + Setup\ Cost \\ & + Holding\ Cost + Construction\ Cost + Time\ Cost \end{aligned} \tag{15}$$

$$Processing\ Cost = \sum_{p}\sum_{k}[V_p\left(\sum_{o}\sum_{i} N_{oik}Y_{poik}\right)] \tag{16}$$

$$Unment\ Demand\ Penalty\ Cost = \sum_{o}\sum_{k}[E_o(E_{ok} - E_{ok})] \tag{17}$$

$$Disposal\ Cost = \sum_{p}\sum_{k}(W_pM_{pk}) \tag{18}$$

$$Holding\ Cost = H(\sum_{i}\sum_{k} F_{ik}) \tag{19}$$

$$Construction\ Cost = \sum_{p}\sum_{k}(G_pR_{pk}) \tag{20}$$

$$Time\ Cost = TM(\sum_{k} FT_k) \tag{21}$$

## 4. Computational results

The model is solved through the General Algebraic Modelling System (GAMS). Hypothetical values are used in the study as shown in Figure 3. These parameters served as the base scenario for the model. The run has three different types of water inputs with varying qualities and quantities for each period. There is a total of three periods tested and the water can undergo three processes with two possible outputs for disposal or reuse. Each output has its own quantity demand and quality requirements. The results of the base run in terms of the breakdown of costs are shown in Figure 3.

| | Output 1 | | Output 2 | |
|---|---|---|---|---|
| **Period** | **Demand** | **Quality** | **Demand** | **Quality** |
| **1** | 500 | 100 | 500 | 150 |
| **2** | 600 | 100 | 400 | 150 |
| **3** | 500 | 100 | 500 | 150 |

| | Demand Input | | |
|---|---|---|---|
| **Period** | **1** | **2** | **3** |
| 1 | 800 | 200 | 100 |
| 2 | 900 | 150 | 70 |
| 3 | 850 | 200 | 50 |

| Process | Setup Cost | Disposal Cost | Processing Time | Processing Cost |
|---|---|---|---|---|
| 1 | 500 | 2000 | 5 | 2 |
| 2 | 600 | 3000 | 10 | 3 |
| 3 | 800 | 3000 | 10 | 3 |

| Output | Penalty Cost | Disposal Cost |
|---|---|---|
| 1 | 500 | 5 |
| 2 | 600 | 3 |

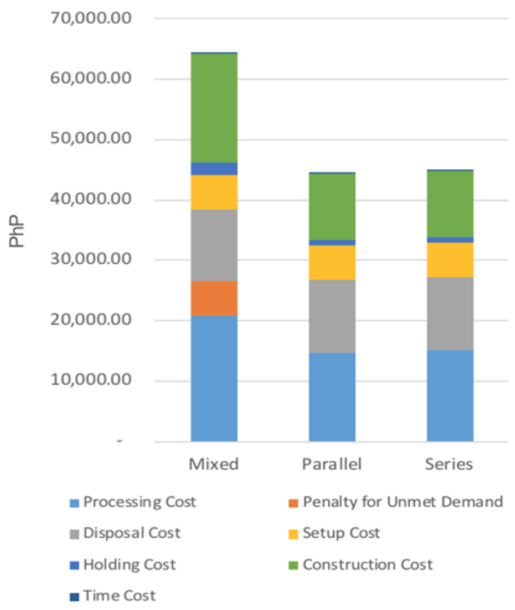

*Figure 3: Case study input parameters and base model results*

From the results of the base run, the most efficient in terms of costs is the parallel input treatment type. This is because the parallel treatment system allows the full efficiency of the system, wherein the different inputs can go to different processes for treatment without having to wait for the previous input as long as allowable by the process flows. As such, the idle time in between treatments are minimized. In the series treatment type, the costs are reduced because of the reduced construction costs. However, the time costs of series are more pronounced due to the longer idle time in between processes. For the mixed treatment type, the capacity requirements of the model are larger because of the total quantity of the three inputs is mixed at the same time. Because of this, the total costs are higher in comparison. However, in a long term setting, the mixed treatment type can be beneficial as the building investments for the infrastructures necessary can be justified. As a result, the total costs for an extended period of time could be less than the parallel and series setups. Other scenarios were tested using the base model as reference. Table 2 summarizes the results from these scenarios.

*Table 2. Scenario Analysis*

| Scenario | Configuration | Findings |
|---|---|---|
| Presence of a higher holding cost | Parallel | The increase in the holding costs pushed the model to increase disposals. The disposal and processing costs increased in order to process as much inputs as possible to refrain from holding any to the next period. |
| Presence of higher cost associated with time | Parallel | Parallel is still the best option because of its capability to treat simultaneous inputs. Series has a greater cost incurred than the parallel configuration because of its constraint to wait for the previous process, which increases its idle time. Although the time cost of the mixed is not as high as the series, it incurs more processing cost overall. More construction costs are required for this mode in order to accommodate the quantity of the mixed inputs. |
| Presence of lower quality requirement | Parallel | The overall costs of all the different processing types have decreased with the decrease of the quality requirement for the first output type by 50 %. Because of this, the processing costs as well as the construction costs have decreased because there is less need for the model to process requirements to meet the quality specifications of the output. |

## 5. Conclusions

A multi-period mathematical model to optimize the wastewater treatment process was formulated in this study. The model considers different input types in terms of quality and quantity as well as different choices for outputs with a set demand or capacity for each period. The unique characteristic of this model is its ability to integrate the front and back end of the treatment process as well as introduce three different modes of input treatment – mixed, parallel, and series. These different input types have varying benefits dependent on the stakeholder of the system. Mixed treatment initially would have a higher cost for the construction but would be justifiable for a long-term basis since processing costs are lesser than its counterparts. However, the mixed treatment overall performs the most poorly out of the three input treatment types. This is because it is unable to efficiently allocate its resources according to the requirements of the outputs. On the other hand, parallel and series treatment require less capacity for each process. However, the time taken to finish may be slightly longer. In the case of the parallel configuration, the delays in terms of time in between processes are reduced as the model is not constricted to waiting for the previous batch of inputs to process. As such, the parallel method is generally more cost and time efficient than the other three. However, in a plant that is underutilized, the series method can also be used.

This study shows that there are alternative input processing types that companies can look into as worth investing on. From the base run and scenario analysis, the different parameter settings have shown that the parallel and series configurations are superior in terms of minimization of costs and efficiency of time. Also, the model formulated is able to distinguish the main components of the costs of each period as well as decide whether investments in the construction of new infrastructure are justifiable given a set time horizon. In future studies, it is recommended to look into the integration of multiple types of quality requirements for a certain output. There will be more than one requirement in terms of quality measure that needs to be met in order for a batch of water to be disposable to a certain site.

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