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Cost-effective wastewater treatment and recycling in mini-plants using mass integration

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Abstract This work illustrates the use of a mass integration approach to cost-effectively reduce wastewater treatment and discharge in mini-industrial plants. The approach focuses on the use of functional analysis, graphical analysis tools, and mathematical formulation to simplify the size of the problem and identify separation/interception scenarios. Sensitivity analysis is then used to compare all potential interception/separation scenarios identified by the analysis tools. The proposed approach is utilized to systematically optimize the cost of wastewater treatment in a fabric plant in Dubai, UAE. The solution involves the use of a settling tank (already exists in the process), reverse osmosis, and an evaporator to minimize the cost of wastewater treatment in the plant for the reduction of biochemical oxygen demand, chemical oxygen demand, total dissolved solids, and total suspended solids.

List of symbols

C	Total annualized cost per flowrate unit
Freshwater	Flowrate of fresh water
$f_{i,S}$	Fraction of stream
h	Value of parameter in fresh water
i	Stream i
int	Refers to a stream or composition after interception/treatment
n	Total number of wastewater streams
m	Total number of sinks
S	Sink
t	Treatment technology
W_i	Flowrate of wastewater stream
WS	Flowrate for a sink
x	Value of parameters in wastewater
y	Value of feasible parameter in sink

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Introduction

Environmental regulations are being enforced in the United Arab Emirates (UAE) and the Arabian Peninsula in general. Wastewater minimization and treatment is one of the most critical subjects that is addressed and controlled under these regulations. Water resources are scarce in this part of the world; however, water demand is on the rise due to increase in population, agriculture, and industrial firms. The water demand in Sharjah, UAE, has doubled in the last 2 years.

Industrial wastewater has been targeted recently by local environmental agencies. There are many mini-industrial plants in UAE and the Arab Peninsula and the number is increasing exponentially every year. Industrial plants in UAE and the Arab Peninsula include textile, food, paint, chemical, and petrochemical plants. Most of these plants were designed without regard to environmental regulations but they have all now to comply with these regulations. Companies operating such small plants cannot afford high costs to handle waste minimization tasks. They are looking for cost-effective solutions to keep the plants in operation while meeting environmental regulations.

Industrial wastewater in UAE can be discharged to sewage if it meets specific values for BOD (biochemical oxygen demand), COD (chemical oxygen demand), TDS (total dissolved solids), and TSS (total suspended solids). Otherwise, the wastewater will have to be transferred to a hazardous waste collection center to be treated. This option is very costly and companies are looking for other solutions. Current approaches that are followed in industry focus on end-of-pipe treatment and vendors are repeatedly offering the same solution to different plants. However, what is needed is a systematic methodology that can be used to identify cost-effective solutions to every plant based on the plant's objectives and process description. In this regard, mass integration provides an attractive framework.

Overview of mass integration analysis

Over the past two decades there has been a significant progress in the area of cost-effective industrial pollution prevention through process integration techniques. Process integration is a holistic approach that relies on using fundamental principles of engineering and science to understand the global picture of flow of mass and energy in the process, so as to identify the target to be attained by process integration. The target could be minimum wastewater discharge (Wang and Smith 1994; Doyle and Smith 1997; El-Halwagi 1997; Hamad et al. 1998; Dunn and

Wenzel 2001; Dunn et al. 2001), minimum heating and cooling utilities (Linnhoff 1993), reactor attainable region (Biegler et al. 1997), minimum waste interception/separation cost (El-Halwagi 1997; Dunn et al. 1999), etc. Once the target has been identified, engineers work with the appropriate level of details, including data measurement and collection, to achieve their process target.

Process integration includes two dimensions: energy integration and mass integration. Energy integration identifies optimal utility usage in the chemical process. Energy integration analysis can be limited to thermal pinch so as to minimize heating/cooling utilities or can be made more comprehensive by incorporating power and fuel (Hohmann 1971; Linnhoff 1993; Shenoy 1995). There is a complementary relationship between mass integration and energy integration. Mass integration (El-Halwagi and Spriggs 1998) tackles energy indirectly and identifies optimal tasks or strategies to be performed by energy integration. Mass integration, a more recent development in process integration, will be utilized in this work to cost-effectively reduce wastewater and organic discharge.

Mass integration refers to the optimal generation, allocation, separation (separation, treatment, and interception are used in this paper interchangeably), and routing of species (including water and contaminants) throughout the chemical/manufacturing process. Significant work was done in the last two decades to tackle pollution prevention systematically and economically using mass integration analysis. The original motivation for this work was using mass separating agents (MSAs) to selectively remove pollutants from gaseous/liquid streams (El-Halwagi and Manousiouthakis 1989) through the concept of a mass exchange network (MEN). This work focused on dealing with specific streams, usually terminal streams, to be treated and discharged/recycled. Usually these streams have specific target compositions. The scope of pollution prevention through mass integration was then extended to include in-process waste interception and allocation (El-Halwagi et al. 1996; El-Halwagi 1997), simultaneous energy and waste minimization (Dunn et al. 1999), simultaneous mass interception and solvent synthesis (Hamad and El-Halwagi 1998), single- and multi-component VOC recovery from gaseous emissions via condensation (Dunn et al. 1995; Dye et al. 1995; Richburg and El-Halwagi 1995; Parthasarathy and El-Halwagi 1999), simultaneous waste reduction and energy integration (Srinivas and El-Halwagi 1994a), chemically reactive separations (El-Halwagi and Srinivas 1992; Srinivas and El-Halwagi 1994b), fixed-load removal (Kiperstock and Sharratt 1995), flexible performance (Papalexandari and Pistikopoulos 1994; Zhu and El-Halwagi 1995; Zhu et al. 1997), and controllable MENs (Huang and Edgar 1995; Huang and Fan 1995). Pressure-driven membrane separations were addressed by Srinivas and El-Halwagi (1993) and El-Halwagi (1992). Crabtree and El-Halwagi (1995) developed a mathematical formulation to synthesize cost-effective environmentally acceptable reactions. Lakshmanan and Biegler (1995) developed reactor-network targeting strategies.

El-Halwagi (1997) and Hamad et al. (1998) discuss several strategies and graphical mass integration tools that can be utilized to provide insightful analysis, reduce the size of the problem, and develop optimal solutions. Some of these strategies and graphical tools will be illustrated and discussed in the following sections.

The essence of this work is to employ mass-integration strategies and graphical tools combined with functional analysis, linear programming, and sensitivity analysis to systematically develop optimal strategies for reducing organic and water discharge from industrial mini-plants. Combining these tools systematically represents a major advantage of this work. An actual industrial fabric plant will be targeted in this work.

Strategies of mass integration

Mass integration relies on two basic steps to identify potential optimal solutions so as to economically minimize wastewater discharge.

Step 1 includes studying the global flow of mass in the process. This step guarantees that the design engineer will explore all potential opportunities that exist in the plant to reduce or eliminate the waste. There are several graphical tools that can be utilized to fulfill this step. Examples include the mass pinch diagram, the water pinch diagram, the path diagram, the source–sink mapping diagram, and the reaction attainable region.

Step 2 includes applying several strategies to achieve the waste reduction target. These strategies include segregation of streams; low-cost process modifications (LCPM); mixing and recycling of streams; interception (separation) on in-plant streams; and high cost process modifications.

Segregation refers to avoiding the mixing of streams. In some industrial applications dilute streams mixed with concentrated streams and even different phases are mixed unnecessarily. Segregation of streams at the source furnishes several opportunities for cost reduction: segregation can generate environmentally benign streams; segregation enhances the opportunities for direct recycling since it is easier to recycle dilute streams than concentrated streams; and segregation results in more concentrated streams, which it is thermodynamically more favorable to intercept/treat using various technologies.

Low-cost process modifications: in some cases, waste can be reduced or eliminated by changing the operating conditions (e.g. temperature, pressure, flowrate, composition) of the unit from which the waste is generated. In other cases, one might replace this unit with a more environmentally benign unit if the cost associated with this change is low.

Mixing and recycling: discharged waste can be reduced by recycling pollutant-laden streams back to the process to be utilized in process or nonprocess requirements. In some instances several streams need to be mixed with each other to achieve the desired level of flowrate and composition. The cost associated with this step includes piping and perhaps mixing tanks.

Interception refers to the utilization of separation technologies to selectively remove the targeted species from the targeted stream(s). In most industrial applications, interception is needed to enhance the opportunities of recycling and to generate environmentally benign streams.

High-cost process modifications: this may include employing new chemistry (such as new solvent, new reaction path, etc.) or new technology (i.e. new plant).

How to use and combine steps 1 and 2 in arriving at optimal solutions will be addressed in a later section when the solution procedure is discussed.

Problem statement

The problem addressed in this work is stated as follows: given a set of wastewater streams in a mini-industrial plant, it is desired to cost-effectively minimize wastewater discharge and fresh water usage in the plant while meeting environmental regulations.

Solution procedure

The solution procedure used in this work relies on the use of the above mentioned strategies. However, to identify when, why, and how to use these strategies, the following tools are used:

1. Functional analysis
2. Graphical analysis tools
3. Linear programming/optimization.

Functional analysis

Function is a master keyword that is embedded in all actions that are carried out in the chemical process design. Each process consists of several pieces of equipment (unit operations) that are utilized to progress from raw material to final product. Each piece of equipment is used to provide a specific function (task) or more than one function. Hence, the process is considered as a set of functions/tasks (tasks and functions are used interchangeably in this paper; Umeda et al. 1972; Gopalkrishnan et al. 1997). Each function should answer the questions when, why, and how with regard to the associated equipment. In order to perform mass integration analysis effectively and globally, the functions that are performed in the process must be identified. Functional analysis will be used in this work for two purposes:

1. Determine the function/task of equipment and unit operations involved in the process. This will allow the design engineer to explore opportunities via the following questions (process simplification):
   a. Is it necessary to perform all of these functions?
   b. Is there another technology that can do the same function at a lower cost?
   c. Can the operating zone of existing units be extended to perform more than one function and hence eliminate some equipment (Gopalakrishnan et al. 1997)?
   d. Can a new technology, which can perform more than one function, be used to reduce the number of items of equipment in the process (Gopalakrishnan et al. 1997)?
   e. How can the process be run continuously or batch-wise to maximize the usage of existing resources?
   f. Are there any other resources in the plant which need to be considered?
2. Identify the functions of graphical tools to be used in the analysis. There are several graphical tools that are available in the literature to be used in mass integration analysis. When the desired functions to be performed by the graphical tools are specified, it should be easier to decide what graphical tools to use or what new tools could be developed.

Graphical analysis tools

Graphical tools could be very helpful in mass integration analysis if selected and used properly. These tools can provide insightful hints toward efficient mass integration analysis to generate optimal solutions. For wastewater minimization, the following functions would be of significant assistance in the analysis if provided by the graphical tools:

1. To study mass propagation in the process
2. To study mass allocation in the process
3. To identify in-plant mass interception opportunities
4. To identify end-of-pipe interception opportunities
5. To identify process modification opportunities
6. To identify wastewater recycling opportunities.

The following tools are found to be efficient to be used in this work for the overall purpose of wastewater minimization.

Mathematical formulation: linear programming

Mathematical formulation is used in this work to model the recycling network so as to minimize the cost of wastewater treatment. Mathematical formulation could be made very complex by including mixed-integer nonlinear constraints or could be simplified to merely focus on linear modeling. In this work, the above-mentioned analysis tools, functional analysis and graphical analysis tools, are used to simplify the mathematical formulation of this problem to fall under the linear programming category. Using linear programming guarantees the global optimum solution for the given constraints and simplifications. Linear programming will be used in this paper to perform the following functions:

1. To identify feasible recycling opportunities so as to maximize wastewater recycling or to minimize wastewater treatment cost
2. To determine mixing and segregation scenarios
3. To determine portions of each stream to be treated and/or recycled
4. To determine total cost of treatment.

The mathematical formulation and linear programming of this problem will be discussed in detail later in the case study.

Mathematical linear programming combined with the above graphical analysis tools and functional analysis provide a flexible approach that allows design engineers to provide their inputs into the analysis while gaining insightful hints to identify optimal strategies and solutions toward achieving the desired target of wastewater minimization. Figure 1 illustrates how the three tools interact to develop optimal solutions. The interaction among these tools is studied in detail through a sensitive analysis methodology. The effectiveness and details of the proposed methodology are illustrated in the following case study.

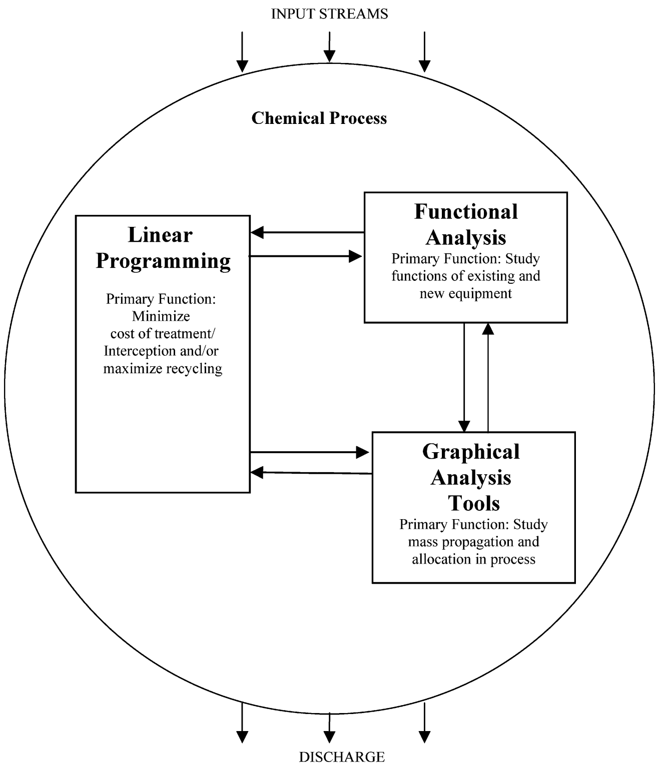

Fig. 1. Interaction between tools used in solution procedure

Case study: wastewater minimization in a mini-fabric plant

Al Naseej Fabric Plant, Dubai, UAE produces 8,000 gal/day (30.28 m3/day) of wastewater. Due to new environmental regulations enforced by the Government of UAE, the plant cannot keep discharging its wastewater to the sewage system in its present condition. The company has two choices. First, pay a large amount of money to ship the wastewater off-site to a hazardous waste collection facility. Second, treat the wastewater stream on-site then discharge it to the sewage system. The second choice sounded more attractive. However, to find the most cost-effective treatment alternative, mass integration-based solutions were sought.

Process description

The plant has a sizing stage where yarn is passed through a size solution, Fig. 2. The size is primarily polyvinyl alcohol (PVA) solution.

The spent size (majority is water, 1,000 gal/day) (3.79 m3/day) is dumped into a sump where it is mixed with boiler water (1,000 gal/day) (3.79 m3/day) and air condition (A/C) blowdown (6,000 gal/day) (22.71 m3/day). The characteristics (parameters) of these streams are presented in Table 1. The wastewater from the sump is then pumped to a settling tank to get rid of heavy organics and solids. The water from the settling tank is then pumped to a collection tank to be dumped into the sewage. The sludge from the settling tank is pumped to evaporation ponds,

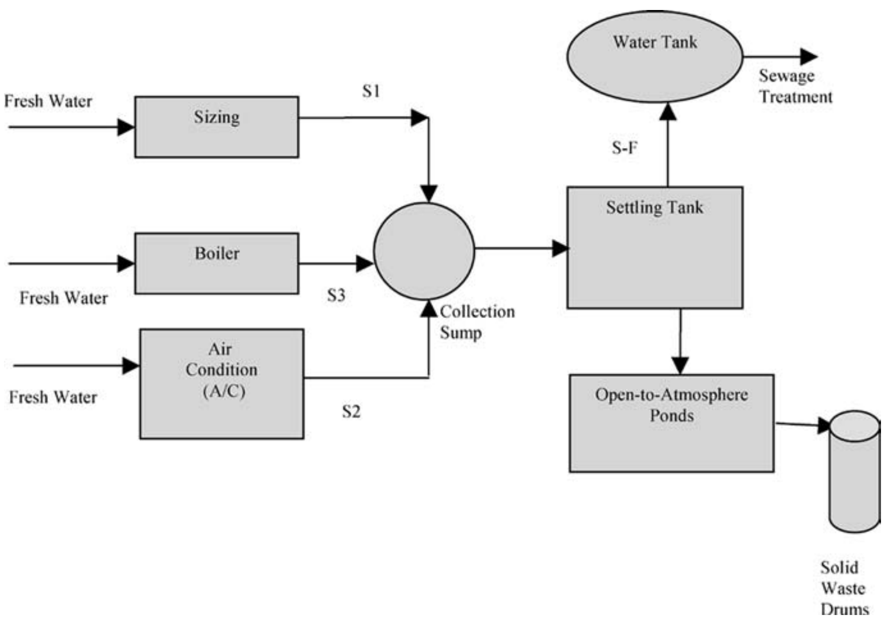

Fig. 2. Water flow diagram in the process

Table 1. Characteristics of wastewater streams

Parameter	Units	Size water (S1)	A/C water (S2)	Boiler water (S3)
Total suspended solids (TSS)	mg/l (ppm)	7,240	62	52
Total dissolved solids (TDS)	mg/l (ppm)	11,500	5,710	1,250
Chemical oxygen demand (COD)	mg/l (ppm)	37,760	38	54
Biochemical oxygen demand (BOD)	mg/l (ppm)	18,600	4	6

Table 2. Characteristics of wastewater stream (S-F)

Parameter	Units	Value
Total suspended solids (TSS)	mg/l (ppm)	102
Total dissolved solids (TDS)	mg/l (ppm)	3,300
Chemical oxygen demand (COD)	mg/l (ppm)	4,600
Biochemical oxygen demand (BOD)	mg/l (ppm)	2,000

Table 3. Environmental target compositions for discharged wastewater streams

Parameter	Units	Value
Total suspended solids (TSS)	mg/l (ppm)	200
Total dissolved solids (TDS)	mg/l (ppm)	3,000
Chemical oxygen demand (COD)	mg/l (ppm)	3,000
Biochemical oxygen demand (BOD)	mg/l (ppm)	1,000

which are open to the atmosphere. Once the majority of the water vaporizes, the solid waste (very concentrated sludge) is transferred to special drums to be sent off-site to a hazardous waste collection. The wastewater stream leaving the settling tank to be dumped into the sewage is the target stream in this study, as mentioned above. This stream does not meet the new environmental regulations and must be treated. The characteristics of this water stream (called S-F, hereafter) are presented in Table 2.

Table 3 includes the environmental target composition for each of the parameters of wastewater streams to be discharged directly to the sewage.

Hence, the S-F stream is over the limits in TDS, COD, and BOD, and cannot be discharged as is to the sewage. In other words, the S-F stream must be treated before it is discharged to the sewage.

Solution methodology

Functional analysis

In this section, functional analysis is considered only for equipment currently used in the process. We are dealing with mini-plants and hence the number of items of equipment involved is small. Only unit operations that generate wastewater (sources) or use water (sinks) will be analyzed. Items of equipment to be considered are sizing unit, A/C, boiler, settling tank, and the evaporation ponds.

Sizing unit

Function	Form coating layer on the yarn
Why	To protect the yarn against snagging or abrasion. Water exists in the size solution
How	Size solution is used with high quality water. Water quality is as follows: - BOD<10 ppm - COD<50 ppm - TDS<500 ppm - TSS<100 ppm
When	Before the yarn gets into knitting
Alternative	No alternative is considered (beyond the scope of this work)

A/C (air conditioning)

Function	To provide cooling
Why	To make atmosphere more suitable to work in
How	Using cooling towers with high quality water. Water quality is as follows: - BOD<10 ppm - COD<50 ppm - TDS<500 ppm - TSS<100 ppm
When	All day
Alternative	No alternative is considered

Boiler

Function	To generate steam
Why	To provide heating to the process
How	By using electricity to boil high quality water. Water quality is as follows: - BOD<10 ppm - COD<50 ppm - TDS<500 ppm - TSS<100 ppm
When	All day
Alternative	No alternative is considered

Settling tank

Function	To settle/stagnate wastewater
Why	To remove bulk of TSS and partially TDS
When	After the sump and before treatment/discharge
Alternative	No need for an alternative

Evaporation (open-to-atmosphere) ponds

Function	To vaporize bulk of water from sludge
Why	To reduce size of sludge
When	After settling tank and before sludge shipped off-site
Alternative	No need for an alternative. However, fans could be used to expedite the process of evaporation

Graphical analysis: parameter path diagram

The path diagram (El-Halwagi et al. 1996; El-Halwagi 1997) represents the flowrate of a stream versus its composition. The diagram could be created for one or two species using an x–y diagram or three species using the triangle diagram (Gopalkrishnan et al. 1997). However, the parameters discussed in this work (BOD, COD,...) are unrelated to each other and their sum is not equal to unity as in the case of species composition. In this work, the concept of a "parameter" path diagram is introduced. A parameter here could represent composition, flowrate, BOD, TDS, pH, flammability, etc. In this paper, it will be used to represent BOD, COD, TDS, and TSS. This diagram has the following characteristics.

1. Each parameter is represented by a "half" axis. For example, the BOD could be the "positive" side of the x-axis and the TSS could be the "negative" side of the x-axis. The scale for each axis is relative.

2. Streams in the process can be represented as a point, a line, a segment of connected lines, or a rectangular. What is important is that each "node or edge" represents a value of a certain parameter(s). The number of nodes or edges for each stream refers to the number of parameters that are of interest in this particular stream. Each node represents two parameters.
3. The set of target parameters can also be represented by a set of connected nodes or edges.
4. A path diagram for each parameter could be developed by connecting the nodes of this parameter for the streams. A path diagram could be developed for each parameter. However, one path diagram is sufficient to represent all parameters since each node is connected to other nodes that represent other parameters.
5. Besides representing process streams (sources) on the diagram, each unit operation that utilizes water (sink) can be represented in terms of a feasible range of parameters, as will be illustrated later. Each sink is also called a generator since it most likely ends up generating a source that can be used in the analysis.

One major advantage of the parameter path diagram is that it encompasses the characteristics of both the path diagram (El-Halwagi et al. 1996; El-Halwagi 1997) and the source–sink diagram (El-Halwagi 1997; Hamad et al. 1998; Dunn and Bush 2001). While the path diagram represents the propagation of species (composition) throughout the process, the source–sink diagram provides insights into recycling opportunities. These characteristics can be simultaneously encompassed in the parameter path diagram.

Parameter path diagram for case study

As mentioned earlier, the sizing wastewater (S1), the A/C wastewater (S2), and the boiler wastewater (S3) are mixed in the sump then pumped to a settling tank. The wastewater stream (S-F) leaving the sump is pumped to a holding tank to be treated, shipped off-site, or discharged to the sewage system if its characteristics allow. The parameter path diagram of this process is shown in Fig. 3. Each line segment in the path diagram represents transformation of parameters and hence represents a unit operation.

In Fig. 3, each stream is represented by a rectangle with four corners. There is one corner in each quarter of the diagram. Each corner represents two parameters. For S1 one corner represents BOD (18,600 ppm) and TDS (11,500 ppm). Another corner represents TDS (11,500 ppm) and TSS (7,240 ppm). The third corner represents TSS (7,240 ppm) and COD (37,760 ppm). The fourth corner represents COD (37,760 ppm) and BOD (18,600 ppm). The same applies to the S-F stream. However, for S2 and S3, only TDS values are of significance compared to TSS, BOD, and COD. Hence, they are represented in the diagram by small circles.

The corners in each quarter can be connected by line segments to represent the path of propagation of parameters in the process. Developing two path diagrams in opposite quarters would represent the propagation of the four considered parameters.

Within Fig. 3, two paths were developed: one path represents the BOD and TDS propagations in the process and the other represents the TSS and COD propagations in the process. Actually, with a closer look, one finds that each path diagram represents the propagation of all four parameters. This is because each node is connected to the other nodes through line segments.

Next, the sinks are added to identify recycling, mixing, segregation, and treatment opportunities. The acceptable limits of the potential sinks (sewage and fresh water) are represented by shaded squares (to distinguish sinks from sources). The shaded large rectangle in the diagram represents the feasible region of each parameter if wastewater is to be discharged to the sewage system. The small shaded diagram represents the quality of water needed for the size solution, boiler, and A/C.

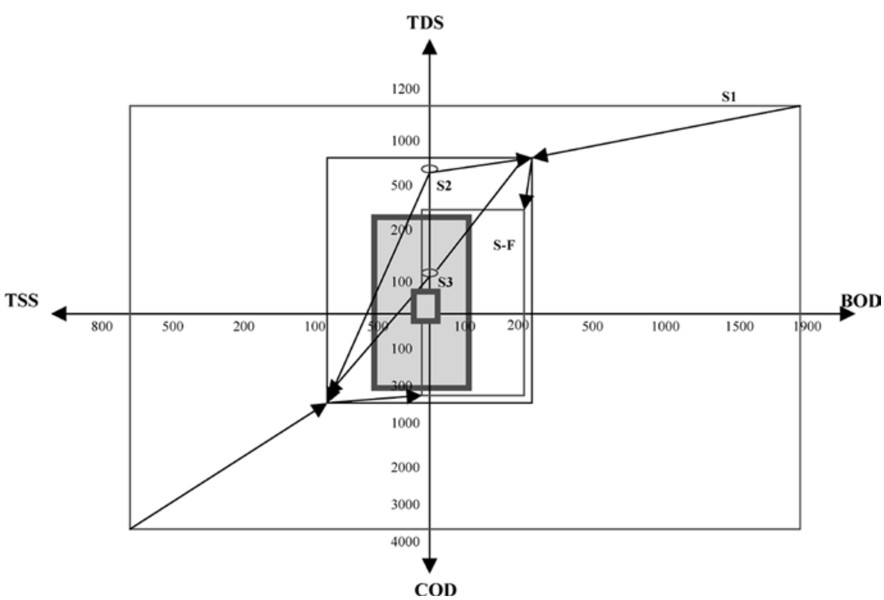

Fig. 3. Parameter path diagram of case study

Insightful analysis

Several insights can be gained from the parameter path diagram. Examples include:

- Any source that lies completely within the boundaries of a sink represents a direct recycling opportunity.
- Any source can be removed left, right, up, or down using separation/interception technologies or by process modifications.
- If the line that connects two sources goes through the boundaries of a sink, then the two sources can be mixed completely or partially to be recycled to that sink.
- Parameter propagation can be studied by developing paths for the parameters by connecting the corners of the sources to represent mass flow in the process. From parameter propagation, process modification, mixing, and separation (interception) opportunities could be identified.

By inspecting the diagram, the following insights can be obtained.

1. The boiler wastewater (S3) can be discharged as is to the sewage system.
2. The A/C wastewater requires only TDS treatment.
3. BOD and COD are the most troublesome parameters in the process.
4. Mixing the streams in the sump generates a large stream with BOD, TDS, TSS, and COD problems.
5. The settling process is efficient in reducing the TDS and TSS of the stream. However, it is not efficient in reducing the COD and BOD of the stream.
6. Streams S2 and S3 can be mixed to reduce overall TDS. The resultant stream has almost zero BOD and zero COD. That in turn means that this stream could be discharged as is to the sewage system or it could be mixed with BOD-laden and/or COD-laden streams to reduce the overall BOD and COD in the resultant stream and hence reduces the cost of treatment.
7. It seems very beneficial to use settling in treating the size wastewater stream.

Insightful potential solutions

From the above analysis, several potential mutually exclusive projects can be envisaged. The following is a list of those projects.

1. Discharge S3 as is to the sewage system.
2. Mix S3 and S2 in proper proportions to create a final stream that can be discharged directly to the sewage system.
3. Treat all or part of S2 for TDS removal.
4. Do not mix streams S2, S3, and S1.
5. Use settling tank to pre-treat S1 (generates new S-F).
6. Mix output stream (new S-F) from 5 with output stream from 2 to generate a final stream that is feasible in terms of BOD and COD to discharge to the sewage system.
7. Use treatment technology to treat S1.
8. Use treatment technology to treat S-F.
9. Use treatment technology to treat new S-F, generated from 5.

As can be deduced from the above analyses, treatment technologies are essentially needed to reduce COD, BOD, and TDS in the discharged wastewater streams. In the following section, those technologies will be superimposed on the parameter path diagram to identify interception opportunities.

Graphical mass interception analysis

Mass interception technologies could be mass- or energy-based technologies. Those technologies can be used to selectively reduce contaminants in wastewater streams such as solids and chemicals (organics and nonorganics) and hence reduce TDS, TSS, COD, and BOD. Examples of mass-based interception technologies include biotreatment, adsorption, stripping, etc. These technologies involve adding a mass separating agent to selectively remove or destroy certain solids or chemicals. Energy-based technologies involve applying cooling, heating, and pressure principles to selectively separate components. Examples include reverse osmosis, condensation, distillation, etc. Figure 4 shows flowrates and values of parameters for all sources and sinks in the process. In order to determine what technologies to use, the functions/tasks to be performed by these technologies must be identified. By inspecting Fig. 4, the following functions are identified:

- To reduce BOD to less than 1,000 ppm
- To reduce TDS to less than 3,000 ppm
- To reduce COD to less than 3,000 ppm
- To reduce TSS to less than 200 ppm.

According to the above functions, the following technologies are utilized in this work to do the analysis and identify the most cost-effective interception network. Removal efficiency for each technology is roughly based on data obtained from ETA-Environmental & Engineering Services Company (ETA-EES), Dubai, United Arab Emirates. In addition, for existing equipment, the same efficiency is used.

1. Biotreatment: mainly to destroy BOD and COD and to a lesser extent to reduce TDS and TSS. 99.5% of BOD and COD removal is used in this work.
2. Evaporation: to remove BOD, COD, TSS, and TDS by concentrating the wastewater to a sludge. 15% of the water is assumed to end up in sludge. 99.9% of all parameters is assumed (in product water).
3. Reverse osmosis: mainly to remove TDS and TSS and to a lesser extent BOD and COD. 60% of treated water is assumed to permeate. The reject (40%) must be treated using evaporation for any further treatment. Removal ratio is assumed to be 99.9% for TDS and TSS.

The operation range of each technology is superimposed on the parameter-path diagram as illustrated in Fig. 4.

Potential interception opportunities

Figure 4 shows that several interception opportunities can be identified to reduce contaminants in wastewater to be discharged to the sewage system or recycled back to the process. Examples include:

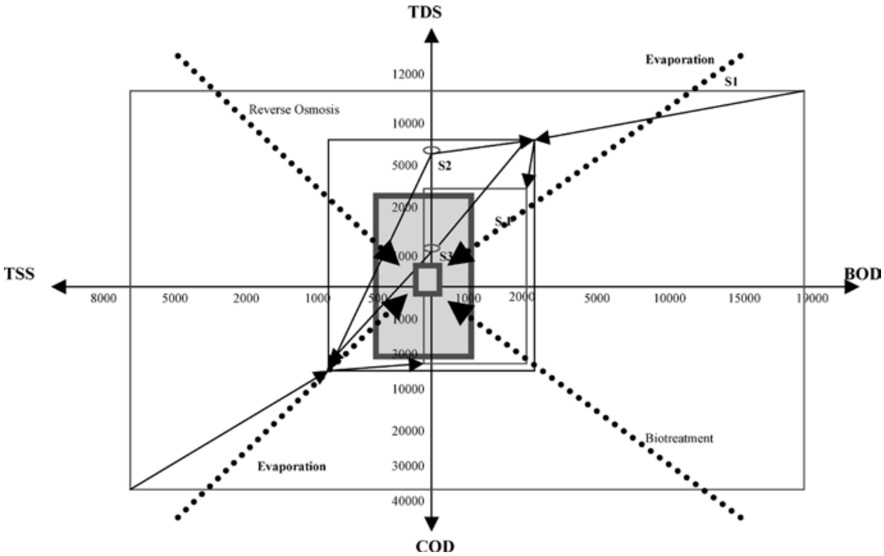

Fig. 4. Parameter path diagram with interception technologies included

- Use biotreatment to reduce BOD and COD in S-F.
- Use evaporation to reduce BOD, COD, TDS, and TSS in S-F.
- Use evaporation to reduce BOD, COD, TDS, and TSS in S1.
- Use biotreatment followed by reverse osmosis to reduce BOD, COD, TDS, and TSS in S1.
- Use reverse osmosis to reduce TDS in S2.
- Use reverse osmosis to reduce TDS in S3.

To decide which interception schemes to pursue, recycling and discharge opportunities must be analyzed, as will be discussed in the following section of the paper.

Recycling/discharge: linear programming

From Fig. 3, several recycling/discharge opportunities could be identified:

- Discharge S3 directly to sewage.
- Mix S2 partially or completely with S3 then discharge.
- Mix S1 partially or completely with stream from 2 then discharge.
- Mix S-F partially or completely with stream from 2 then discharge.

In this work, the total flowrate and parameters of each process stream are fixed. The ratio of each stream that will be recycled, mixed, or discharged will be determined through optimization. This means that the path of each stream is fixed. This is a valid approach since we are dealing with mini-plants. This approach could be expanded to include nonlinear optimization, which is beyond the scope of this work.

Mathematical formulation

Let $x_{i,j}$ refer to parameter j for stream i before and after treatment and W_i refer to total flowrate of stream i. Let $f_{i,S}$ refer to the fraction of stream i that will go to sink (unit operation) S before or after treatment. Each sink S has a certain maximum limit, $y_{S,j}$, that it can tolerate for each parameter, j. In addition, each sink has certain flowrate that it can process, WS_S. If a stream is treated, then the superscript int is used. Fresh water can also have certain values for each parameter, h_j. Flowrate of fresh water to sink S is denoted by $\mathrm{Freshwater}_S$.

- Objective function: maximize (water recycling+direct wastewater discharge)
- OR: minimize cost of treatment/interception

$$\mathrm{Max} = \sum_{S=1}^{S=m} \sum_{i=1}^{i=n} f_{i,S} W_i$$

for i=1, 2,..., n and S=1, 2, ..., m

$$\mathrm{OR} : \mathrm{Min} = \sum_{i=1}^{n} C_{t,i} \left(1 - \sum_{S=1}^{S=m} f_{i,S} \right) W_i$$

where $C_{t,i}$ is the total annualized cost per unit flowrate of potential treatment technology t to treat steam i. Treatment technology can be different from one stream to another and it must be specified ahead of writing the mathematical formulation. If cost of fresh water is a major concern, then it can be easily added to the objective function.

Subject to:

$$\sum_{i=1}^{i=n} f_{i,S} x_{i,j} W_i + \sum_{i=1}^{i=n} f_{i,S}^{\mathrm{int}} x_{i,t,j}^{\mathrm{int}} W_i + h_j \mathrm{Freshwater}_S \leq y_{S,j} \mathrm{WS}_S$$

$$\sum_{i=1}^{i=n} f_{i,S} W_i + \sum_{i=1}^{i=n} f_{i,S}^{\mathrm{int}} W_i + \mathrm{Freshwater}_S = \mathrm{WS}_S$$

$$\sum_{S=1}^{S=m} f_{i,S} + \sum_{S=1}^{S=m} f_{i,S}^{\mathrm{int}} = 1$$

Optimum solution using sensitivity analysis

The procedure to follow to identify the optimum design is outlined in Fig. 5.

1. Define new interception network

Since this paper deals with mini-plants and hence small number of wastewater streams, all potential interception networks using candidate interception technologies can be easily identified. Hence, using the results of the above analyses, the optimum solution is embedded in Fig. 6.

Using Fig. 6, the following scenarios are identified:

1. Use the settling tank to reduce TDS and TSS in the size solution.
2. By-pass a fraction of S-F and a fraction of S2 and all S3.
3. Treat other fractions of S-F and S2 using reverse osmosis, biotreatment, or evaporation. The following are potential interception/treatment scenarios:
   a. Treat combined S-F and S2 using evaporation.
   b. Treat S2 using reverse osmosis and S-F using evaporation.
   c. Treat S-F using biotreatment to remove BOD and COD. Then mix with S2 and treat using evaporation.
   d. Treat S-F using biotreatment to remove BOD and COD. Then mix with S2 and treat using reverse osmosis.
4. Mix exit stream from interception network with the by-pass stream from 2 and discharge directly to the sewage.
5. Sludge (hazardous waste) production is assumed to be the same in all scenarios of separation since sludge is mainly caused by S1.

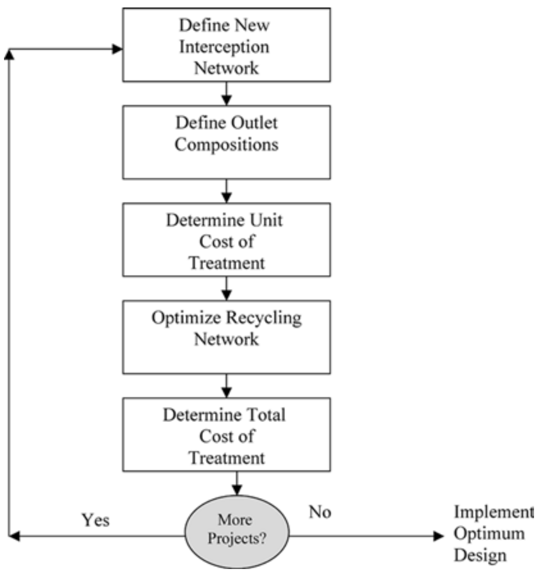

Fig. 5. Optimization scheme through sensitivity analysis

2. Define outlet compositions

Once the interception scheme is identified, then vendor data or experimental results can be used to determine the outlet composition of each interception technology. The outlet composition is referred to by $x^{\text{int}}_{i,t,j}$, where i refers to stream i, t refers to technology t, and j refers to parameter j, in the mathematical formulation. x^{int} is determined as follows for each treatment technology (using ETA-EES data):

- Reverse osmosis: removal ratio is assumed to be 99.9% for TDS and TSS. 40% rejection is assumed.
- Biotreatment: 99.5% BOD and COD removal ratio.
- Evaporation: 99.9% removal of all parameters (85% of water recovery is used).

3. Determine unit cost of treatment

Vendor data from ETA-EES are utilized to determine the cost for treating each stream using a specific technology. The total annualized cost ($C_{t,i}$) should be given in terms of cost (U.S. dollars) per unit flow rate for treating stream i using treatment technology t. The total annualized cost for each technology includes operating and capitals costs. Capital costs are depreciated over 3 years.

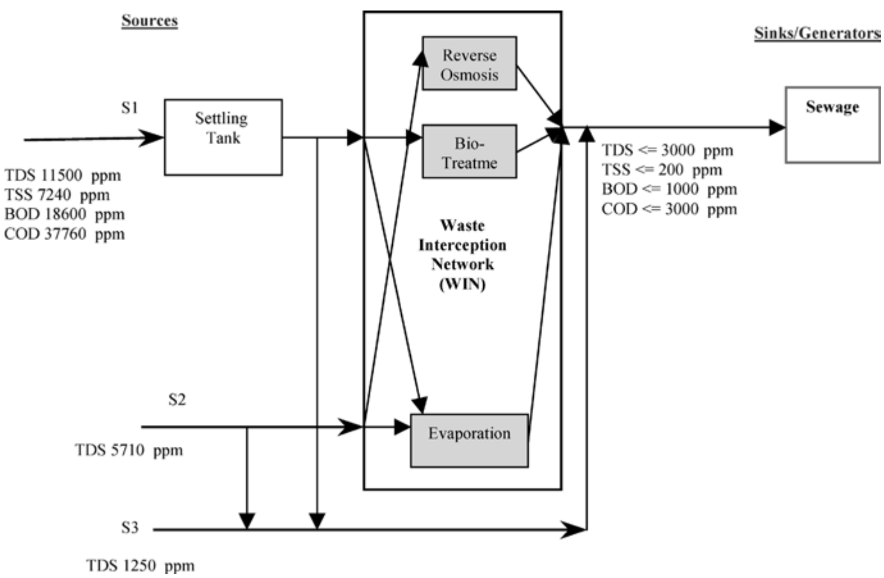

Fig. 6. Schematic representation of potential solutions

- Reverse osmosis: U.S.$0.074/gal (U.S.$19.55/m3)
- Biotreatment: U.S.$0.164/gal (U.S.$43.33/m3) (requires highly skilled labor)
- Evaporation: U.S.$0.145/gal (U.S.$38.31/m3).

4. Optimize recycling/treatment network
Once steps 1–3 have been defined, the linear mathematical formulation discussed earlier can be used to identify the optimal recycling/interception network.

5. Determine total cost of treatment
Once the recycling/interception network is outlined, the total cost is determined through the mathematical formulation.

6. Implement optimum design
When all interception scenarios that were identified in step 1 are evaluated, we select the most cost-effective design and investigate its implementation.

Optimum design of case study
The final solution is illustrated in Fig. 7. In the solution:

1. All S3, 54.8% of S2 and 50.6% of S-F (S1 after settling tank) are by-passed to the collection sump without treatment.
2. The balance (45.2%) of S2 is treated using reverse osmosis.
3. The reject of S2 in RO and the balance of S-F are treated using an evaporation column to produce very pure water and to concentrate solids and organics.
4. Product water from 2 and 3 is recycled to the collection sump.
5. Water from the collection sump is discharged to the sewage with the following composition:
   a. BOD: 1,000 ppm
   b. COD: 2,318 ppm
   c. TDS: 3,000 ppm
   d. TSS: 40 ppm
6. Total annualized cost is U.S.$155,125 (U.S.$425/day).

Conclusion

Mass integration tools have been applied systematically to optimize wastewater treatment cost and wastewater discharge in a mini-fabric plant. The solution involves settling of the sizing wastewater stream to remove the majority of TSS and TDS from the stream. Reverse osmosis and evaporation are added to partially treat the wastewater streams to meet targeted environmental compositions. Segregation, recycling, and mixing strategies are used to reduce the cost of treatment. A parameter path diagram is introduced to systematically reduce the size of the problem and to develop solutions for interception, recycling, and discharge. In this work, mass integration is applied in a new simplified manner that can be easily adapted by process engineers in industry. A sensitive analysis based on an iterative scheme between functional analysis, graphical analysis tools, and mathematical formulation is used to develop the optimal cost-effective solutions to minimize wastewater discharge. Functional analysis and graphical tools are used to linearize and simplify the mathematical formulation. It is worth mentioning that similar results can be obtained using nonlinear mixed-integer programming (El-Halwagi

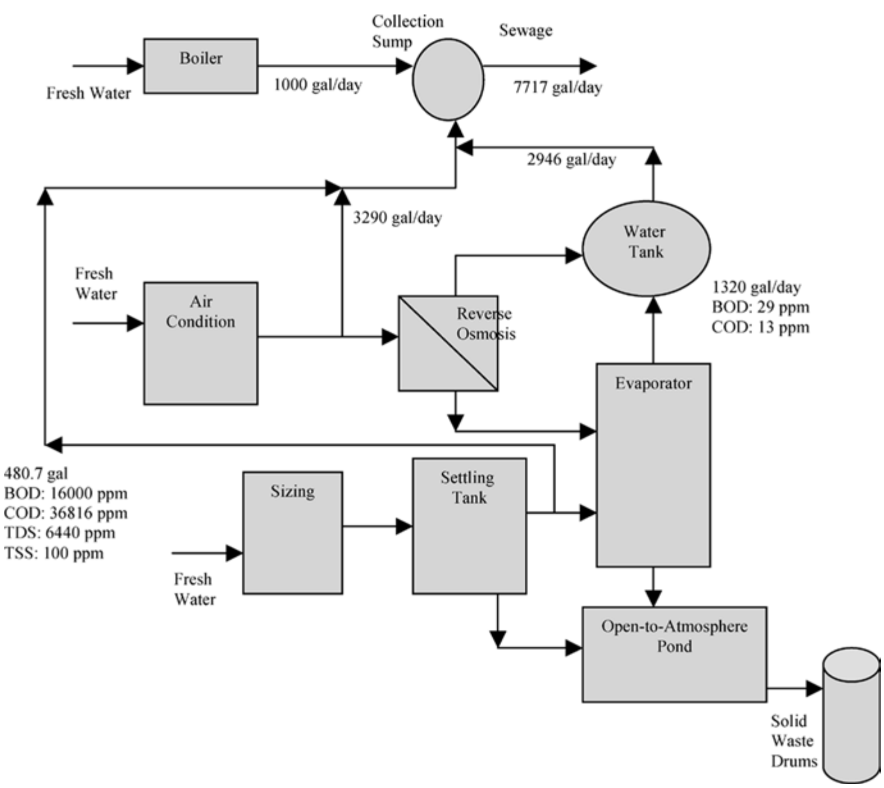

Fig. 7. Optimal solution of case study

et al. 1996; Doyle and Smith 1997) if all alternatives are modeled in the optimization program.

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