ENVIRONMENTAL OPTIMISATION OF RELEASES FROM INDUSTRIAL SITES INTO A LINEAR RECEIVING BODY

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Abstract - Changes to environmental legislation are setting new challenges to both operators and regulators. Optimisation tools can help to turn subjective standards such as Best Practicable Environmental Option (BPEO) (HMIP, 1994: Sharratt, 1995) into more objective ones. Mixed Integer Non Linear Programming (MINLP) is used in this work to optimise overall environmental performance for a group of plants. These plants discharge their final effluents to the same receiving body - a river. The optimisation considers not only the possible configurations within each plant but also the behaviour of the receiving body. A two-stage optimisation is used. Examples illustrate the features of the model.

INTRODUCTION

The problem considers several industrial sites which may discharge liquid effluents at a number of points along a one dimension receiving body - a river. A pollutant has to be removed from these discharges to prevent its concentration anywhere in the river exceeding a defined standard. Pollutant removal is assumed to be achieved at each site in a mass-exchange network (MEN). The optimisation aims to find the minimum total cost (operating + investment) to achieve the standard.

In developing synthesis methodologies it is highly desirable to identify those properties that help reduce the scale of the combinatorial problem (El-Halwagi and Manousiouthakis, 1990). This reduction can be achieved by dividing the global problem into a number of more simple ones. Therefore, to tackle this problem, a two-stage approach was used. In the first stage each site's MEN was optimised for a range of possible discharge levels. This allowed construction of a cost-load function for each plant. These cost-load functions were then used in the second stage. Here, both the discharge points into the river and the pollutant loads released from the plants were variables. Knowing the optimal discharge for each site, the internal (MEN) configuration for each site could be found simply by referring back to the result of the first stage.

DESCRIPTION OF THE PROBLEM

Consider a set of industrial plants $P = \{P_p \mid p = 1 .. NP\}$ discharging their liquid effluents into a river. A set $RB = \{RB_r \mid r = 1 .. NRB\}$ of sections exist in the water stream, where the effluents from the elements of P can be discharged (Figure 1). Plants are only allowed to discharge at certain points along the river. These points are defined in set $POSDIS=\{(P_p,RB_r) \mid P_p \in P, RB_r \in RB, \text{ and a discharge from } P_p \text{ to } RB_r \text{ is possible}\}$. Each plant P_p has a set $R_{pi} = \{R_{pi} \mid i = 1 .. NR_p\}$ of rich streams (effluents) containing pollutant and a set $S_p = \{S_{pj} \mid j = 1 .. NS_p\}$ of lean streams capable of removing the pollutant from the rich streams. The rich streams have fixed mass flow rates G_{pi} and initial concentrations YS_{pi} of pollutant. Their discharge compositions YD_{pi} are variable and will depend on the MEN and discharge arrangement to be chosen. The lean streams, also called mass separating agents (MSA), have variable mass flow rates L_{pj}, limited by upper bounds LU_{pj}. Their supply composition XS_{pj} are fixed and their final compositions XT_{pj} are limited by an operational upper value XUT_{pj}.

The rich streams of a specific plant P_p, after passing through the MEN, are mixed into a single waste stream which can be split into several final discharges. Each has a flow rate EF_{pr} and can be directed into any section RB_r in the water stream.The final load of the pollutant, leaving the plant is:

$$\text{FinaLoad}_p = YE_p \cdot \sum_r EF_{pr} \tag{1}$$

To the flowrate FI_r entering a section in the water stream, are added discharges $\sum_p EF_{pr}$ from the plants. Between discharge points, the flow rate is augmented by a riverside contribution per unit of length, CONF.

Each lean stream is associated with an operational cost. The key pollutant is transferred from the rich streams to the lean streams in countercurrent mass exchangers. This equipment has an annualised cost which depends on its size. The pipework from plants to final discharge points also has a cost. The objective is to find the minimum global annualised costs (over all plants) that will keep the concentration of the key component, at any point of the receiving
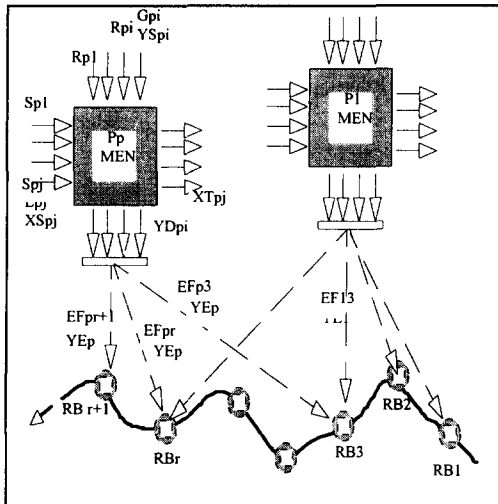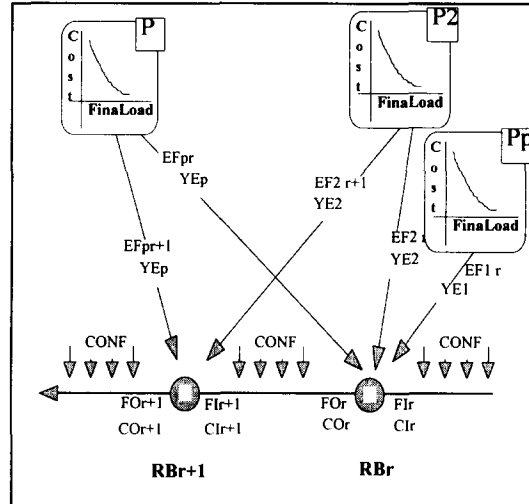
Figure 1 Description of the problem

Figure 2 Schematic representation of second stage

body, below a predefined value.

FIRST STAGE: PLANT OPTIMISATION

The aim is to construct a relationship between the final load of the key pollutant released by each plant, and the cost of achieving that load. For this, a series of optimisation runs were performed. For each MEN, the minimum cost was obtained as a function of its possible final discharge loads.

$$COST_p = f(FinaLoad_p) \qquad (2)$$

The minimisation of the cost, for the various final loads, for each plant, was performed using the generalised match-network hyperstructure (Papalexandri et al., 1994). This approach presents some advantages over to the pinch approach used by other authors (El-Halwagi and Manousiouthakis, 1989; 1990; Kiperstok and Sharratt, 1995). A major one is the ease with which the discharge concentration of the key pollutant can be considered as a variable in the MINLP. This greatly simplifies the construction of the cost-load functions.

Assumptions

The assumptions considered for each of the plants' MENs, are similar to those used elsewhere (Papalexandri et al., 1994; El-Halwagi and Manousiouthakis, 1990):

1. The mass flow rate of each stream remains essentially unchanged throughout the network.
2. All the required separation duties are based on the exchange of a single (key) component, not depending on the presence of other solutes.
3. Mixing of different streams is only allowed for the rich streams just before they leave the plant.
4. In the range of compositions involved, the equilibrium relation governing the distribution of the key component between the i th rich stream and the j th lean one were linear i.e.

$$Y_{pi} = m_{pij} \cdot X_{pj} + B_{pij} \quad (p \in P_p, \ i \ = \ 1,2 \ .. \ NR_p \ and \ j \ = \ 1,2 \ .. \ NS_p) \qquad (3)$$

where both m_{pij} and b_{pij} constants whose values depend on the characteristics of the system involving the key solute, the rich and the lean stream.

5. The lean streams are considered as once-through MSAs. Regeneration and recycling of the MSAs is not considered.
6. The MENs operate under constant pressure and temperature.
7. All mass exchanges are counter-current.

The above assumptions reduce the complexity of the problem and the computational effort, but are nevertheless reasonably realistic

SECOND STAGE: GLOBAL OPTIMISATION

The second stage of the problem is illustrated schematically in Figure 2.

Assumptions

The following assumptions are made for the second stage of the problem:

1- The receiving body behaves as a one dimensional water stream. Its characteristics are only computed at a set of locations along its axis (RB_r s).

2- The water stream receives contributions of clean water (without the key pollutant), between the RB_r s
3- Plants can only discharge their effluents in the RB_r s.
4- Each plant can discharge its effluents into one or more RB_r s.
5- The key pollutant does not undergo any decay process in the receiving body.
6- Costs for the pipework are function only of the distance between plant and point of discharge.

Formulation of the second stage of the model
The second stage of the model is also formulated as a MINLP. The elements of this model are:

VARIABLES
β_{pr} - Binary variable, denotes the existence (1) or not (0) of a discharge from plant P_p to section RB_r.
FO_r - Flow rate of the water stream leaving section RB_r.
FI_r - Flow rate of the water stream entering section RB_r.
CO_r - Concentration of key component in the water stream leaving section RB_r.
CI_r - Concentration of key component in the water stream entering section RB_r.
EF_{pr} - Flow rate of aqueous effluent from plant P_p discharging into RB_r.
YEF_p - Concentration of key component in the aqueous effluent from plant P_p.
$COST_p$ - Cost of MEN in plant P_p, obtained from the first stage of the solution as a function of $FinaLoad_p$
$FinaLoad_p$ - Load of key component leaving plant P_p.
TotalCost - Total annualised cost, includes operational and annualised capital costs of MEN and final effluents pipeworks.

CONSTANTS
G_p - Total flow rate of aqueous effluents from plant Pp.
$DRB_{r'r}$ - Distance from section $RB_{r'}$ to section RB_r of the receiving body.
DtD_{pr} - Distance from plant P_p to Section RB_r of the receiving body.
CONF - Flowrate of inflow contributions of clean water into the receiving body, per unit of distance.
INIF - Initial flow rate of the receiving body.
INIC - Initial concentration of key component in the receiving body.
PIPECOST - Cost of pipework per unit of length
ALLOWCONC - Maximum allowable concentration of key pollutant in the receiving body (the quality target).

OBJECTIVE
The objective is set as the minimum cost necessary to achieve a given maximum concentration of the key pollutant in the river:
Minimise
   TotalCost = Annualised cost of MEN in all plants + Annualised cost of discharge pipework

$$TotalCost = \sum_{Pp \in P} COST_p + \sum_{(Pp \in POSDIS)} \sum_{(RBr \in POSDIS)} \beta_{pr} \cdot DtD_{pr} \cdot PIPECOS \tag{4}$$

   The first term of the equation, annualised cost of the MEN, originates from the first stage of the solution, plant optimisation (Equation 2). The second term expresses the cost of the pipework selected to link plants and discharge points.

CONSTRAINTS
a- Mass balances at each final plant mixer

$$G_p - \sum_{RBr \in POSDIS} EF_{pr} = 0 \qquad P_p \in P \tag{5}$$

b- Component balances at each final plant mixer

$$FinaLoad_p - YEF_p \cdot \sum_{RBr \in POSDIS} EF_{pr} = 0 \qquad P_p \in P \tag{6}$$

c- Mass balances at each discharge point

$$\sum_{Pp\epsilon POSDIS} EF_{pr} + FI_r - FO_r = 0 \qquad RB_r \ \epsilon \ R \tag{7}$$

d- Component balances at each discharge point

$$\sum_{Pp\epsilon POSDIS} EF_{pr} \cdot YEF_p + FI_r \cdot CI_r - FO_r \cdot CO_r = 0 \qquad RB_r \ \epsilon \ R \tag{8}$$

e- Mass balances between discharge points

$$\left(FO_{r'} + CONF \cdot DRB_{r'r} \right) - FI_r = 0 \qquad RB_{r'}, RB_r \ \epsilon \ RB \text{ and } RB_r \text{ is next to } RB_{r'} \text{ (downstream)} \tag{9}$$

f- Component balances between discharge points

$$FO_{r'} \cdot CO_{r'} - FI_r \cdot CI_r = 0 \qquad RB_{r'}, RB_r \ \epsilon \ RB \text{ and } RB_r \text{ is next to } RB_{r'} \text{ (downstream)} \tag{10}$$

g- Logical constraint connecting flow rate of effluent from a plant to a section of the receiving body with the existance of this discharge

$$EF_{pr} - \beta_{pr} \cdot \left(1.1 \cdot G_p \right) \leq 0 \qquad \left(P_p, RB_r \right) \ \epsilon \ POSDI \tag{11}$$

Where, $(1.1 \cdot G_p)$ is used as a large positive number to force β_{pr} to assume the value 1 whenever $EF_{pr} > 0$.

Further constraints were included as bounds to the values of some of the variables.

e- Maximum concentration of key pollutant in the receiving body

$$CO_r \leq ALLOWCONC \quad , \qquad CI_r \leq ALLOWCONC \qquad RB_r \ \epsilon \ R \tag{12}$$

f- Limits for the final loads of key pollutant obtained from the characteristics of the plants' MEN in the first stage of the solution

$$FinaLoad_p \geq LowerLimit \quad , \qquad FinaLoad_p \leq UpperLimit \qquad P_p \ \epsilon \ P \tag{13}$$

EXAMPLE I, simultaneous optimisation of four plants

This examples considers four industrial sites, P_1, P_2, P_3 and P_4 discharging their effluents into a river. For the purposes of this example, P_1 is the same as P_3 and P_2 is like P_4. They all have a pair of effluents, R_1 and R_2, carrying a key pollutant which can be transferred to a pair of lean streams, S_1 and S_2, through a MEN. The data for this streams are largely based on the work of El-Halwagi and Manousiouthakis, 1990. Data are shown in Table 1.

TABLE 1 Characteristics of the streams

		Rich Streams			Lean Streams		
		G_{pi} kg/s	YS_{pi} w/w		LU_{pj} kg/s	XS_{pj} w/w	XUT_{pj} w/w
Plants	R1	0.25	0.13	L1	0.30	0.03	0.06
P_1 & P_3	R2	0.10	0.06	L2	0.90	0.001	0.03
Plants	R1	0.25	0.13	L1	0.70	0.03	0.06
P_2 & P_4	R2	0.10	0.06	L2	0.90	0.001	0.03

Lean stream S_1 is used as extractant in perforated plates exchangers. S_2 is used in packed columns. The mass transfer coefficient Kya, for these is given by the following expressions:

Kya $= 0.685GE^{0.47}$ Kg of pollutant / $m^3s \, \Delta y$ for the R_1-S_2 systems,

Kya $= 0.333GE^{0.5}$ Kg of pollutant / $m^3s \, \Delta y$ for the R_2-S_2 systems.

Equilibrium relations controlling the mass transfer of the key pollutant from rich to lean streams are:

for R_1-S_1	for R_1-S_2	for R_2-S_1	for R_2-S_2
$Y_1 = 0.734X_1 + 0.001$	$Y_1 = 0.111X_2 + 0.008$	$Y_2 = 0.734X_1 + 0.001$	$Y_2 = 0.148X_2 + 0.013$

For all plants, the cost of the perforated-plates columns was given by $332,500(NST)^{0.74}$S and the cost of packed columns by $420,000(HK)^{0.81}$S (NST is the number of plates, HK is the height of the packed column in meters and S is the cross section in square meters). Mass separating agent S_1 costed 0.01$/kg and S_2 costed 0.0095 $/kg. Capital was

amortized over 10 years with an annual interest rate of 10% and no final salvage value. For all calculations, operation was for 8760 hours per year. Pipework costed $437/m (PIPECOST).

A small river received the discharges of all four plants. The thirteen possible discharge points are 200 m. apart from each other and are numbered from RB_0 to RB_{12}. The plants are located according to Figure 3. Distances from each plant to the receiving body points are given in Table 2.

The maximum allowed concentration of the key pollutant in the river was fixed at 0.008 w/w. RB_0 was considered to be the initial point of the river, therefore, no former contributions exist. Inflows of fresh water from the riversides were assumed to be 0.0040 m^3/sec per m of river.

First stage, plant optimisation

At this first stage a relationship is sought between the final load of the key pollutant, released by each plant, and the cost of achieving it, in the plant's MEN. The hyperstructure model was run for values of FinaLoad ranging from 0.0185 to 0.0385 kg/s, for each plant, These being the extremes of zero and maximum treatment. Results allowed the correlation of $COST_p$ as functions of FinaLoad :

$$COST_1 = COST_3 = 2412.63exp(-163.24FinaLoad) - 15940.50FinaLoad + 610.08 \quad (14)$$
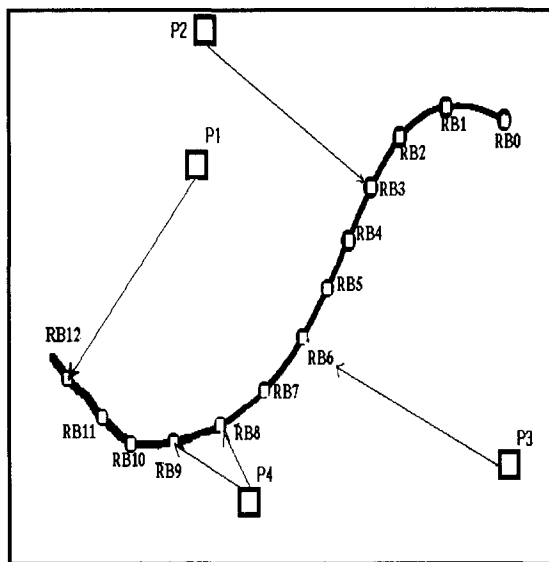$$COST_2 = COST_4 = 1828.47exp(-191.32FinaLoad) - 15285.20FinaLoad + 589.48 \quad (15)$$

Figure 3 Schematic location of plants, discharge points and selected discharges

TABLE 2 Pipework distances from plants to receiving body points, in m.

Discharge points	Plants			
	P_1	P_2	P_3	P_4
RB_0	800	1420	1410	900
RB_1	720	1320	1380	870
RB_2	610	1220	1330	840
RB_3	500	**1220**	1300	750
RB_4	420	1320	1220	640
RB_5	440	1420	1180	490
RB_6	490	1570	**1180**	360
RB_7	500	1660	1300	250
RB_8	500	1780	1450	**160**
RB_9	500	1850	1580	**290**
RB_{10}	480	1900	1700	410
RB_{11}	450	1940	1800	580
RB_{12}	**500**	2000	1930	740

Second stage, global optimisation

The model the second stage was run using Equations 14 and 15 to represent the plants. Figure 3 shows the selected discharge points. In the optimal solution, 37% of the initial pollutant load was removed by the MEN in plants P_1 and P_3. Removal was of 49% for plants P_2 and P_4. Costs are shown in Figure 4 and the river conditions in Figure 5.

EXAMPLE II, successive optimisation of four plants

Example I depicted an unusual situation. Four industrial sites optimised their pollution control facilities simultaneously. More commonly, plants are obliged to adapt their releases to conditions found in the receiving bodies at the time they apply for of their environmental authorisations. We now contemplate this situation for the same four plants and river as the first example.

In this example, plants were installed in the order: P_1, P_4, P_3 and P_2 at the same locations as Example I. At the time of their installation, each plant had to meet the same objective by setting an appropiate discharge load and location. The concentration of the key pollutant at any point of the river could not exceed 0.008 w/w. When P_1 was installed, no other plant was operating. When P_4 was installed the optimum solution was found for the situation where plant P_1 was already operating and releasing its effluents. The same approach was followed for the other two plants. The models already described, were used to find the optimum solution for each plant. However, existing plants' releases were fixed to the values they were authorised to operate. Results are compared to those found in Example I (simultaneous case).
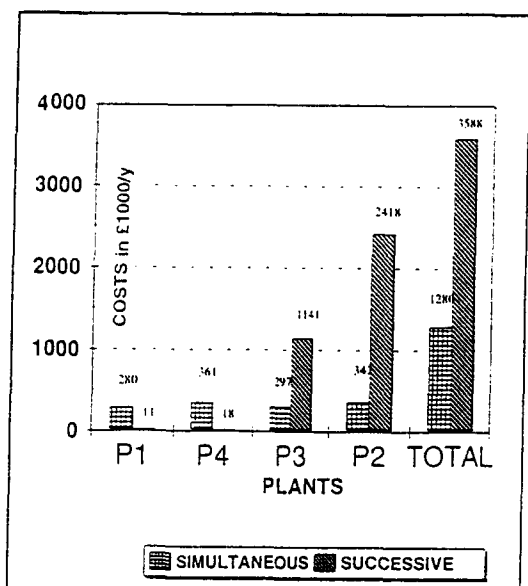
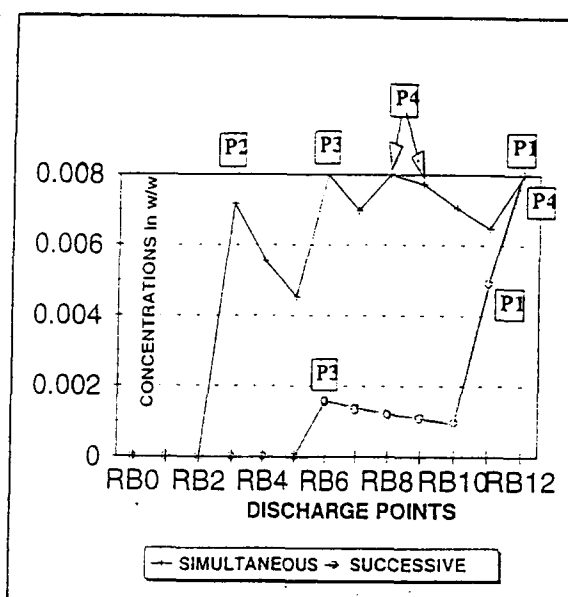Figure 4 Comparison of costs, Simultaneous vs Successive cases

Figure 5 Concentrations in river, Simultaneous vs Successive cases

In the successive case, the first two plants P_1 and P_4 take full advantage of the dilution capabilities of the river. No pollutant removal is needed in these two plants. When plant P_3 installs the limits for the final release of the key pollutant has to be relaxed beyond the initial 0.0185 kg/s used in Example 1 . The cost function had to be extrapolated beyond its original limits, to estimate the cost. For plant P_2, no feasible solution was found -in other words, this plant would have to produce a zero discharge to meet the river quality standard. Again, using the same cost function, the cost of zero discharge was estimated. The values presented show that it would be much more sensible for plants P_3 and P_2 to invest in abatement equipment in plants P_4 and P_1 (if possible), in order to achieve a more cost effective solution (Figure 4).

The conditions in the river may be found in Figure 5. It may be seen that the river's capabilities are poorly exploited in the successive case.

CONCLUSIONS

Optimisation models can be used to improve the enforcement of environmental legislation where "best" technologies and "acceptable" costs are demanded. Considering the receiving environment together with the abatement design within the individual plants allows solutions with significantly lower environmental impacts at the same cost. The study shows that the use of optimisation tools for design can be moved outside the boundaries of an individual plant or site. The consideration of the combined environmental impact of several plants allows the tradeoff of pollution control cost between the sites. For the case considered, which is typical of industrial development along a river, large potential cost savings and environmental improvements can be identified. The use of a cost-load function provides a well defined and useful link between plant and environment.

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