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Short note

Assessing the sensitivity of water networks to noisy mass loads using Monte Carlo simulation

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Abstract

For many water-intensive processes, water reuse can reduce water consumption as well as effluent generation. Process integration approach based on graphical pinch methodology for targeting and water network synthesis is often employed. The integrity of water network design to achieve the minimum water targets is highly sensitive to the availability of reliable process data. Existing network design process, however, assume that process data are fixed and well-defined, whereas the actual operating conditions such as water flowrate and the corresponding mass loads may fluctuate over time. These fluctuations in processing conditions can lead to process disruptions and product quality problems. This work demonstrates the use of Monte Carlo simulation in assessing the vulnerability of water networks to noisy mass loads. A case study illustrates the procedure of selecting the most robust network configuration from three alternative designs that achieve comparable water savings.
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Keywords: Process integration; Water network; Reliability; Monte Carlo simulation; Mass load fluctuation; Mass transfer water-using processes

1. Introduction

Many industries utilise large quantities of water for washing or rinsing of raw materials and process equipment. Examples of specific water-intensive activities include pulp washing operations in paper production, surface cleaning pretreatment in electroplating industries, and clean-in-place procedures in food processing. Environmental concerns pertaining to fresh water supply sustainability and effluent discharge impacts have encouraged industries to use process integration techniques to reduce both plant water requirements and wastewater volume.

In practice, process integration projects may either be integrated into grassroots process design or implemented through process retrofit. The latter scenario is often encountered when water supply or effluent treatment capacity suddenly changes relative to desired production capacity. For instance, when an increase in production volume is intended, the existing wastewater treatment plant may be taxed beyond its limits due to the increase in process water volume. Hence, plant retrofits will become necessary to keep the aggregate effluent volume within practical limits. This reduction can often be achieved without modifying individual unit operations simply by recycling partially contaminated process water through a suitable network.

Techniques involving water network synthesis are generally categorised as graphical-based and mathematical optimisation-based. Graphical-based procedures are normally associated with the well-known *water pinch analysis*, which has evolved from the thermal pinch analysis (Linnhoff et al., 1982). A two-stage procedure is normally employed to synthesise a maximum water network, i.e. minimum utilities (fresh water consumption and wastewater generation) targeting and network design (Almutlaq & El-Halwagi, in press; Almutlaq, Kazantzi, & El-Halwagi, 2005; Aly, Abeer, & Awad, 2005; Castro, Matos, Fernandes, & Nunes, 1999; Dhole, Ramchandani, Tainsh, & Wasilewski, 1996; Dunn & Wenzel, 2001; El-Halwagi, Gabriel, & Harrel, 2003; Feng & Seider, 2001; Foo, Manan, & Tan, 2005; Hallale,

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2002; Kuo & Smith, 1998; Manan, Tan, & Foo, 2004; Olesen & Polley, 1997; Parthasarathy & Krishnagopalan, 2001; Polley & Polley, 2000; Sorin & Bédard, 1999; Wang & Smith, 1994). Mathematical optimisation-based methods, on the other hand, supplement the graphical approach by including other design constrains, e.g. forbidden match, safety, controllability, fluctuating mass load, etc. into the water network synthesis (Bagajewicz & Savelski, 2001; Benko, Rév, & Fonyó, 2000; Benko, Rév, Szitkai, & Fonyó, 1999; Dunn, Wenzel, & Overcash, 2001; Huang, Chang, Ling, & Chang, 1999; Koppol, Bagajewicz, Dericks, & Savelski, 2003; Prakotpol & Srinophakun, 2004; Savelski & Bagajewicz, 2000a,b, 2001; Shafier, Domenech, Koteles, & Paris, 2004; Takama, Kuriyama, Shiroko, & Umeda, 1980a,b, 1981; Tan, 2002; Tan & Cruz, 2004; Tsai & Chang, 2001; Yang, Lou, & Huang, 2000; Zhou, Lou, & Huang, 2001). Some works have also seen the combination use of the above two techniques (Alva-Argáez, Kokossis, & Smith, 1998; Alva-Argáez, Vallianatos, & Kokossis, 1999; Jacob, Kaipe, Couderc, & Paris, 2002). This enables a wider range of problems to be addressed and explored.

Water-using operations in a process plant can generally be classified into mass transfer-based (e.g. desalter in refinery, pulp washing in paper mill, surface cleaning in electroplating industries, etc.) and non-mass transfer-based operations (e.g. water being fed as a raw material, or being withdrawn as a product or a by-product in a chemical reaction, or being utilised as heating or cooling media). Recent works on water network synthesis showed that emphasis on this area has been moved from mass transfer-based operations into non-mass transfer-based operations (e.g. Dhole et al., 1996; El-Halwagi et al., 2003; Hallale, 2002; Manan et al., 2004). However, there remain rooms for improvement for water network with mass transfer-based operations, particularly in the area of mass load fluctuation. This is the subject of this paper.

A mass transfer-based water-using operation is characterised by the preferential transfer of species from a rich stream to water, which is being utilised as a lean stream or a mass separating agent. The basic model of a water-using process as a mass exchanger is shown in Fig. 1. The water functions as a lean stream to absorb a solute or contaminant from a rich stream, which is the material being processed or cleaned. In the representation of water network, the rich streams usually are not shown (Wang & Smith, 1994).

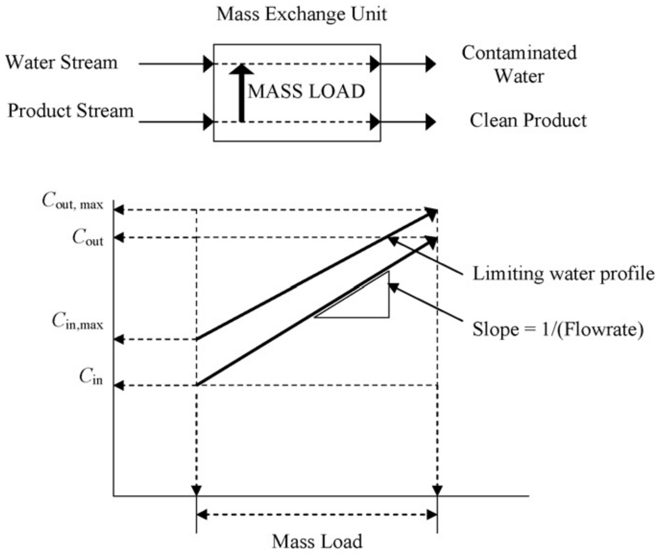

Fig. 1. Water-using process as a mass exchanger (Wang & Smith, 1994).

In practice, one of the key factors in determining the success of a process integration project is the availability of reliable process data to be used for design calculations (Wenzel, Dunn, Gottrup, & Kringelum, 2002). However, such data is not always obtainable. One of the main reasons companies resist the use of process integration is the apprehension about possible adverse effects on process conditions and product quality. Thus, a procedure for assessing the reliability of designs prior to their actual implementation is essential to making process integration schemes more acceptable. In the pioneering work of thermal pinch analysis, Hohmann (1971) applied simulation techniques to assess the effect of unexpected variations in operating conditions on heat exchange network. That approach made use of the assumption of steady-state operation away from the intended design conditions, rather than explicit dynamic modelling; a similar approach is used in this study. In any conventional water network analysis, these design data will always take the theoretical maximum inlet and outlet composition for a given mass transfer process, after considering the various operation factors such as corrosion and fouling limits. This is termed as the *limiting data* (Wang & Smith, 1994). However, in actual process operation, mass transfer processes are always subject to considerable process disturbances (termed as “noise”), e.g. varying mass load due to irregular process stream flowrate. Hence, the design of a robust water network entails explicitly including process variability in the model formulation.

Design loads can, of course, incorporate safety factors based on information on load variability. However, such safety factors are determined without prior knowledge of network layout. Moreover each water-using process is assumed to be independent of the others. The limitation of this approach is that, the processes in a water network are not isolated. Mass load variations in one unit may propagate through the network via recycle streams and upset other processes.

In the case where mass loads are below the design load, a “cleaner” waste stream from the water network is encountered. On the other hand, when mass loads from the process streams exceed the design load, this leads to product quality as well as process disruption problems. Tan and Cruz (2004) proposed the use of fuzzy linear programming to synthesise robust networks. However, that method does not allow for the assessment of a network that has already been designed, for instance by the use of any of the methods previously described. Hence, this also gives rise to the necessity of simulating the behaviour of the integrated network under conditions of noisy mass loads. This problem has previously been addressed by Tan (2002) using fuzzy or possibilistic reliability theory. Although numerically efficient and effective, the principal difficulty with that approach was that fuzzy reliability theory remains to be relatively little-known among engineers, giving rise to difficulty in interpreting results.

Hence, another more commonly accepted method, i.e. Monte Carlo simulation is introduced here to provide an alternative solution to the problem.

2. Monte Carlo simulation

Monte Carlo simulation is a numerical procedure for predicting the statistical properties of the outputs of a system based on information on the probability distributions of certain inputs. The approach is employed in many types of mathematical models where analytic prediction of the output statistics becomes intractable due to the system complexity. The procedure is straightforward and easily implemented with computer aids. Use of Monte Carlo simulation is traditionally associated with business or economic applications (Moore & Weatherford, 2001). Engineering uses are also possible with this procedure.

Monte Carlo is based on the repeated computation of system outputs for a number of iterations or samples. A random number generator is used to specify the model input values based on *a priori* probability distributions of these parameters. For each randomly generated set of inputs, a corresponding set of outputs are computed by the model. Once all iterations are completed, the outputs are compiled and statistical properties such as sample mean and standard deviation are calculated using conventional methods. The general procedure for Monte Carlo simulation is shown in Fig. 2. Various statistical tests can also be performed on the outputs, depending on the information desired. Graphical displays such as histograms are also useful for visualising the output probability distributions. Such displays can be used in conjunction with percentiles to estimate the probability of an output values that will fall within a certain range of values. This option facilitates the use of Monte Carlo in assessing the reliability of systems. For example it becomes possible to predict the probability that the actual mass load on a water-using system will exceed its design capacity.

In this work, Monte Carlo is used for assessing the reliability of water network with varying mass loads on its mass transfer-based processes. Mass loads in such plants vary as a result of changes in the quality of the solute-rich stream in contact with the water, which can be the raw material or product in various stages of processing. Thus, mass loads tend to have greater variability than other operating parameters such as stream flowrates, which for instance can be controlled with pumps and valves (Bagajewicz, 2000). It is assumed that the probability distributions of the mass loads are known. Network configurations are designed using various aforementioned design techniques. As is often the case, a given water network problem can have multiple solutions (Bagajewicz & Savelski, 2001; Dunn & Wenzel, 2001), with the final choice of network being made based on other design considerations such as cost and simplicity. Monte Carlo allows the network options to be compared on the basis of robustness, or resistance to variations outside of design conditions. The objective of the procedure is to allow the designer to select a network configuration with the lowest probability of failure, which may occur when a stream concentration exceeds the design inlet or outlet concentration limits.

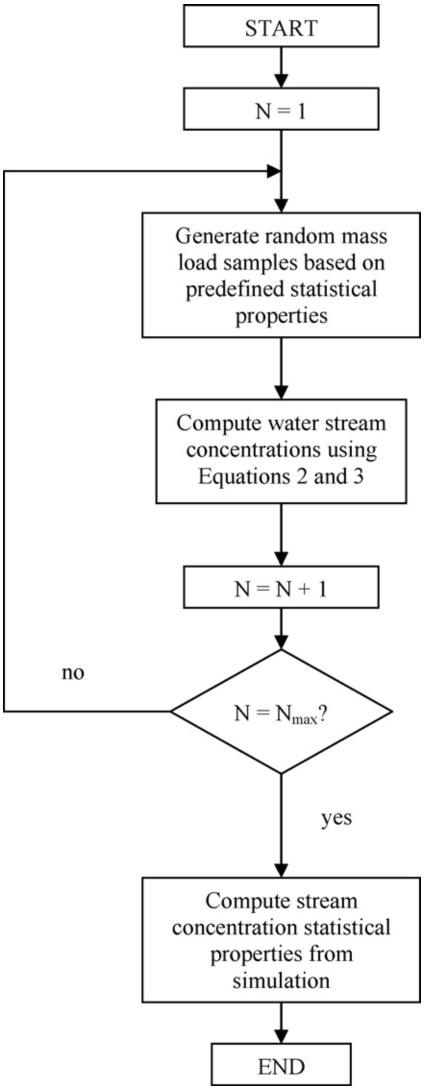

Fig. 2. Monte Carlo simulation flowchart.

3. Case study

The use of Monte Carlo simulation for testing the robustness of alternative water network designs is illustrated using the classical four-process case study from Wang and Smith (1994). The design parameters are given in Table 1. The limiting inlet and outlet concentrations are assumed fixed by existing process conditions, and the fresh water supply is also assumed to have zero concentration. However, unlike the original case study, the mass loads are assumed to be variable with lognormal probability distributions. The mean mass loads and their standard deviations are specified in Table 1. Furthermore, the mass loads of processes 2 and 4 are assumed to be correlated. This situation might occur, for example, when the same rich (product) stream passes through processes 2 and 4 in series, as shown in Fig. 3. The correlation would then exist since the quantity of contaminant loads in processes 2 and 4 are related to the product stream common to both mass exchange units. Thus, mass load that exceed the average design loads will tend to occur at the same time in these two water-using processes. This effect is

Table 1
Design data for example (based on Wang & Smith, 1994)

Process	Maximum inlet concentration (mg/l)	Maximum outlet concentration (mg/l)	Design mass load (kg/h)	Mean mass load (kg/h)	Mass load standard deviation (kg/h)	Distribution	Correlation
1	0	100	2.0	1.6	0.2	Lognormal	None
2	50	100	5.0	3.0	1	Lognormal	Correlated with 4 ($r = 0.7$)
3	50	800	30.0	22.0	4	Lognormal	None
4	400	800	4.0	3.0	0.5	Lognormal	Correlated with 2 ($r = 0.7$)

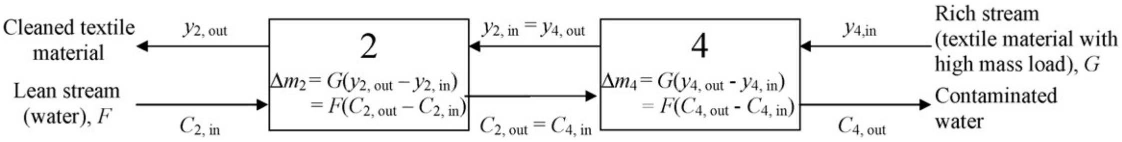

Fig. 3. Two processes linked by both lean and rich streams.

similar to correlated heat loads, which have been noted as being problematic in the heat integration literature (Perkins, 1999). For example, in a textile plant the product might undergo a two-stage washing process to remove contaminants. In this scenario it is likely that a high mass load in the first washing stage (brought about by excess contaminant in the textiles) will tend to result in a high mass load in the second stage as well. In practice, such correlations can be determined empirically from historical process data along with means and standard deviations. In general, the correlation coefficient $r_{x,y}$ between any two quantities x and y can be calculated from repeated measurements or observations using Eq. (1), as follows:

$$r_{x,y} = \frac{\sum_i (x_i - \bar{X})(y_i - \bar{Y})}{s_x s_y} \tag{1}$$

where x_i is the value of x for observation i; $\bar{X}$ the average value of x; y_i the value of y for observation i; $\bar{Y}$ the average value of y; s_x the standard deviation of x; s_y is the standard deviation of y.

In the context of the process integration problem, the correlated mass loads of two different processes replace the quantities x and y in Eq. (1). In the hypothetical case shown here, the mass loads in processes 2 and 4 are assumed to have a correlation coefficient of 0.7. Due to the variability of the mass loads, safety factors are used for targeting and network design. In this example, the network is designed to be able to absorb mass loads of two standard deviations in excess of the mean values. The design mass loads are identical to the values originally used. The target fresh water demand for the case study is 90 t/h (Wang & Smith, 1994).

It is not uncommon that a given target fresh water demand can be met by a number of different network configurations. It has been shown previously by Dunn and Wenzel (2001) that this case study consists of at least 10 different alternative network configurations. For simplicity, only three of its alternative designs are shown (Figs. 4–6); flowrates are indicated in tonnes per hour. Since the alternative networks are equivalent in terms of the water savings achieved, the choice of network for implementation rests on other engineering considerations such as cost, complexity or space availability. In the current situation, the selection will be based on network reliability. Once the network configurations are specified it is possible to express stream concentrations as functions of the mass loads using simple material balance equations. Input stream concentrations are determined directly from the flowrates and concentrations of the source streams using material balances for stream mixing (recall that

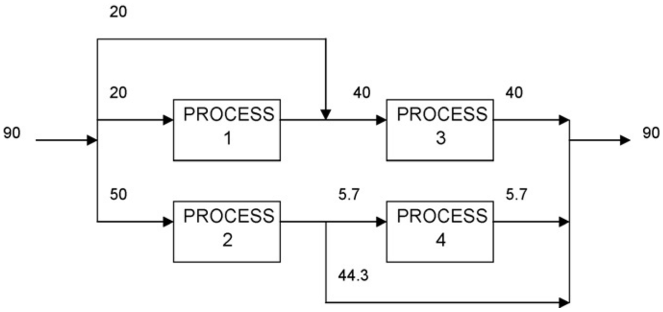

Fig. 4. Network design A (Wang & Smith, 1994).

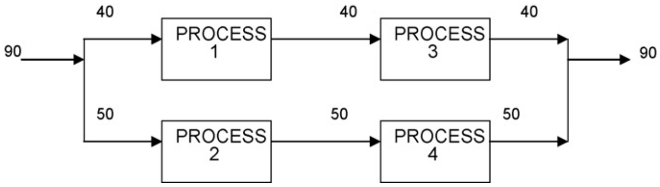

Fig. 5. Network design B (Olesen & Polley, 1997).

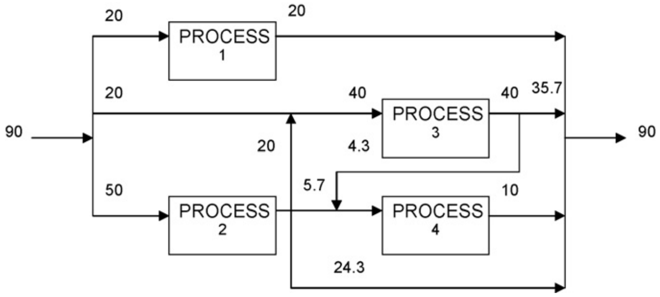

Fig. 6. Network design C (adapted from Dunn & Wenzel, 2001).

Table 2
Results of one simulation iteration

Process	Mass load (kg/h)		Inlet concentration (mg/l)		Outlet concentration (mg/l)	
	Design value	Simulated value	Design value	Simulated value	Design value	Simulated value
1	2.0	1.600	0	0	100	80.165
2	5.0	3.977	50	0	100	79.538
3	30.0	21.484	50	40.083	800	577.176
4	4.0	3.461	400	79.538	800	686.736

fresh water is supplied at 0 ppm), as follows:

$$C_{i,\text{in}} = \frac{\sum_j F_{i,j} C_{j,\text{out}}}{F_i + \sum_j F_{i,j}} \tag{2}$$

where $C_{i,\text{in}}$ is the concentration of inlet stream into process i; F_i the flowrate of fresh water feed into process i; $F_{i,j}$ the flowrate of water reuse stream from process j to i; C_j is the concentration of outlet stream from process j.

Note that Eq. (2) has taken the consideration where fresh water is supplied at 0 ppm. On the other hand, output stream concentrations in turn are entirely dependent on the corresponding input stream concentrations and mass loads of associated processes, described by Eq. (3):

$$C_{i,\text{out}} = C_{i,\text{in}} + \frac{\Delta m_i}{F_i + \sum_j F_{i,j}} \tag{3}$$

where $C_{i,\text{out}}$ is the concentration of outlet stream exiting process i and Δm_i is the mass load added to water stream in process i.

Note that in both Eqs. (1) and (2) the expression $(F_i + \sum_j F_{ij})$ denotes the total water passing through a given process i. This total flowrate consists of freshwater plus reuse water; as in the basic mass transfer model, it is assumed that no solvent loss occurs in the processes, so that inlet and outlet stream flowrates are identical (Wang & Smith, 1994).

Monte Carlo simulation was performed using Crystal Ball (Moore & Weatherford, 2001) to determine the variability of the process stream concentrations in response to mass load noise. One thousand simulation iterations were performed on each network design. Failure of a design occurs when any of the process stream concentration exceeds its limiting data reported in Table 1. Failure in this case is defined as in the robustness analysis of Hohmann (1971), wherein the process operates at pseudosteady state at conditions other than what it was designed for. This definition is applicable when the duration of disturbances (e.g. in process mass loads) are of much greater magnitude than the lag times encountered in the process. Such conditions may occur, for instance, when mass load variations arise from agricultural raw material quality changes as a result of seasonal climatic effects. Application of Monte Carlo simulation for testing the robustness of alternative network designs is illustrated with three different network configurations. The network designs all achieve the same flowrate target of 90 t/h.

3.1. Network configuration A

Network design A, based on the solution developed by Wang and Smith (1994), is shown in Fig. 4. Result of the first simulation iteration using Monte Carlo simulation is shown in Table 2. As shown, composition of all inlet and outlet streams falls below its respective design value (limiting data). This is mainly due to the simulated value for mass loads in all water-using processes that is much lower that its design value. However this is not often the case. Occasionally, simulated mass load values may exceed its design value due to the assigned standard deviation in each of these processes (shown in Table 1). In such a case, the outlet concentration of the process will exceed its design value and the network will experience a “failure” situation.

Probability distributions of the process stream concentrations (excluding the inlet streams of process 1 and 2) after the 1000 iterations are shown in Fig. 7, and a summary of the simulation results is given in Table 3. For the inlet streams, the probability of failure for processes 1, 2 and 4 are zero or negligible. In the case of processes 1 and 2, which are fed with fresh water, this is to be expected. For process 4 draws its feed directly from the outlet stream of process 2, which falls well below the limiting inlet concentration of 400 mg/l. On the other hand, the feed into process three is a mixture of freshwater and discharge from process 1. The mixed stream has mean predicted concentration of roughly 40 mg/l and a standard deviation of about 5 mg/l. The probability that the concentration will exceed the design limit of 50 mg/l is 4%. The outlet stream concentrations of network design A are all saturated, or designed to be at the limiting levels based on the design mass loads. Because of the safety factors, mean concentrations still fall well below these limits. However, the probability that these limits are exceeded due to mass load

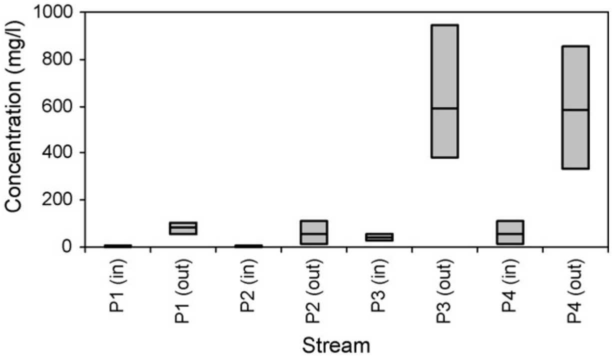

Fig. 7. Stream concentrations for network A.

Table 3
Summary of simulation results for network designs A and B

Process	Flowrate (t/h)	Inlet concentration			Outlet concentration		
		Mean (mg/l)	Standard deviation (mg/l)	Failure probability (%)	Mean (mg/l)	Standard deviation (mg/l)	Failure probability (%)
(A)							
1	20	0.0	0.0	0.0	79.7	10.3	4.0
2	50	0.0	0.0	0.0	58.3	19.3	4.4
3	40	39.9	5.2	4.0	593.2	100.1	2.3
4	5.7	58.3	19.3	0.0	582.9	105.5	3.2
(B)							
1	40	0.0	0.0	0.0	40.0	4.9	0.0
2	50	0.0	0.0	0.0	60.1	21.2	4.3
3	40	40.0	4.9	3.7	592.4	101.8	3.4
4	50	60.1	21.2	0.0	120.3	29.1	0.0

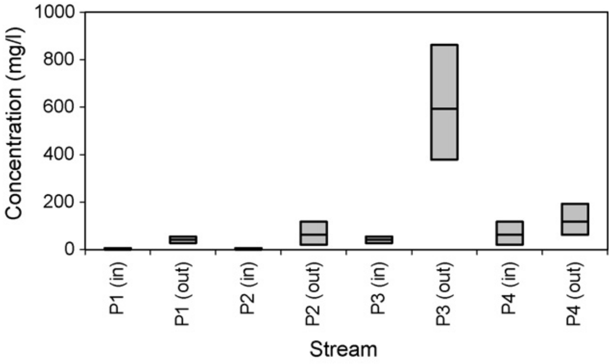

Fig. 8. Stream concentrations for network B.

variations in the system ranges from 2.3% for process 3 to 4.4% for process 2.

3.2. *Network configuration B*

Network design B is based on the solution of Olesen and Polley (1997). The network configuration, shown in Fig. 5 is much simpler than the previous solution. Probability distributions of the stream concentrations, also excluding the fresh water feeds into processes 1 and 2, are shown in Fig. 8, while summary statistics are given in Table 4. Results for the inlet streams are similar to those for network design A, with processes 1, 2 and 4 having zero or negligible probability of failure. The mean concentration of the feed into process 3 is about 40 mg/l and the standard deviation is 5 mg/l, giving a failure probability of just under 4%. Mean outlet stream concentrations and standard deviations of processes 2 and 3 are similar to those in design A, thus giving comparable failure probabilities. On the other hand, the flowrates through processes 1 and 4 are significantly larger than required. This allows better dilution of the mass loads, so that the mean concentrations are well below the design limits. As a result, the probability that these limits will be exceeded during operation is negligible for both of these processes. Network design B is essentially a simplified version of design A. The simplification results in improvement in robustness, with five out of eight streams having zero or negligible failure probability as compared to three for the more complicated design in network A (Wang & Smith, 1994).

3.3. *Network configuration C*

A third network design based on a simplified version of the one proposed by Dunn and Wenzel (2001) is shown in Fig. 6. In this case each stream recycling from a given process outlet to its own inlet has been removed for simplicity. Simulation results are shown in Fig. 9 and Table 4. This design is significantly different from the previous two. Process 1 is fed with fresh water and discharges directly to the effluent stream. The outlet stream of process 2 is split into streams entering processes 3 and 4 and the final effluent, while a portion of the discharge of process 3 is reused in process 4. As with the previous designs,

Table 4
Summary of simulation results for network design C

Process	Flowrate (t/h)	Inlet concentration			Outlet concentration		
		Mean (mg/l)	Standard deviation (mg/l)	Failure probability (%)	Mean (mg/l)	Standard deviation (mg/l)	Failure probability (%)
1	20	0.0	0.0	0.0	78.9	10.1	2.7
2	50	0.0	0.0	0.0	60.1	20.6	3.2
3	40	30.1	10.3	3.4	582.8	103.6	1.6
4	10	284.9	46.9	0.0	588.0	75.6	0.9

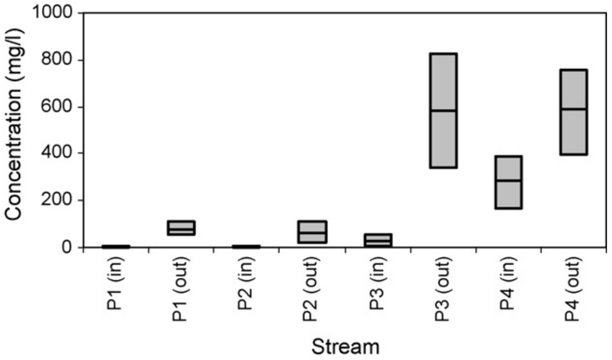

Fig. 9. Stream concentrations for network C.

the concentrations of the inlet streams of process 1, 2 and 4 have zero or negligible probability of exceeding the design limits. The mean concentration of the stream entering process 3 is roughly 30 mg/l, as compared to about 40 mg/l for the previous two designs, but the variability is much greater, with a standard deviation of about 10 mg/l. The probability that its concentration exceeds the design limit of 50 mg/l is slightly lower than the other two designs at 3.4%. Mean concentration levels and standard deviations of outlet streams are very similar to those of design A, except in the case of process 4 where the standard deviation is 25% lower. This decrease in variability gives a failure probability of under 1%. This effect can be traced to the fact that the feed into process 4 is a mixture of streams drawn from the outlets of processes 2 and 3. In contrast, in the previous two designs the feed into process 4 is derived entirely from process 2. Note that the case study assumes a positive correlation between the mass loads of processes 2 and 4. This assumption implies that above-average mass load fluctuations in process 2 are associated with similar large load levels in process 4. The correlation results in an amplification effect when these fluctuations occur simultaneously in the two processes connected in series. The amplification is reduced in design C because of the dilution effect of mixing outlet streams from processes 2 and 3.

These results also reveal some principles that can prove useful for guiding the network design process. As illustrated by the superior robustness of network design B to design A, it is useful to use more than the minimum water flow required in a given unit process. In network B, the flowrates through processes 1 and 4 are 40 and 50 t/h, as compared to 20 and 5.7 t/h for the same processes in network B. Note that this result is achieved even though the total water demand is identical (90 t/h) for both networks. Greater flowrates through processes 1 and 4 in network B water allows for dilution of mass load and gives a process the ability to absorb fluctuations without exceeding the concentration design limits. For particularly critical processes in a plant, networks whose stream concentrations fall well below the limiting values should be favoured as these will be more robust under conditions of variable mass loads. Another key point can be found by comparing the robustness of process 4 in designs A and C. Despite similar mean outlet stream concentrations for the two designs, design C is less likely to fail under noisy load because it draws its feed from two separate sources. In general this shows that it is unfavourable to connect in series two processes with positively correlated mass loads, since high or above-average load levels tend to occur simultaneously to overload the system. Positive correlations in mass load can arise when a common material stream is treated in sequence by two water-using processes, as shown for instance in Fig. 3. The effect can be dampened by avoiding such connections altogether, or, as in the case of design C, by mixing a second stream from an uncorrelated process into the feed of the downstream unit process. On the other hand this result also signifies that it is favourable to connect two processes in series when their mass loads are negatively correlated, since the fluctuations in their mass loads will tend to cancel out.

The use of Monte Carlo has been used to simulate the behaviour of an integrated water network that features mass transfer-based water-using processes. The main concern in this kind of water network is the mass load that is transferred from the process-rich streams to the process-lean (water) streams. Any mass load that exceeds the design value will affect the product quality and process stability.

Future work on Monte Carlo simulation techniques should focus on expanded models wherein variations in other process parameters, such as stream flowrates and feed water quality, are taken into account. Dynamic modelling approaches can also be developed in cases wherein information on network geometry is more complete. Such an approach will entail accounting for time lags in the propagation of the stream concentration fluctuations.

This concept can be well extended to the non-mass transfer-based water-using processes. Hallale (2002) as well as Manan et al. (2004) individually pointed that in non-mass transfer-based water-using processes, water flowrate is more important than the amount of mass load accumulated. Also, a non-mass transfer-based process can have different inlet and outlet flowrates. This inconsistency will surely affect any water recycling loops that present. If a mass transfer-based water-using process is found in the network, product quality of the rich stream associated with this mass transfer operation will also be affected, as the mass load pick up is also a function of the lean stream flowrate. Finally, additional application of Monte Carlo simulation in other applications such as hydrogen integration within oil refineries or water-using batch plants need to be developed. This scope of work will be explored in the future work.

4. Conclusion

The use of Monte Carlo simulation for testing the robustness of alternative water network designs has been demonstrated. The methodology shown allows designers to test alternatives that achieve similar water reduction targets but may potentially differ in terms of vulnerability to mass load fluctuations. The network sensitivity to noise cannot be directly deduced from the mass load variations within individual processes due to the interconnected nature of these units. Fluctuations in stream concentrations are determined not just by mass load variations within isolated process units, but also by the cumulative variations within the entire network due to the presence of water recycle streams.

Further analysis of the relative merits of the alternative network designs requires the identification of the minimum significant failure probability (or, alternatively, reliability) for each process. These threshold values will of course depend on how critical a given process is with respect to a plant's overall operations. Monte Carlo simulation as shown here allows an effective and economical means of evaluating these failure probabilities for comparison with predefined threshold or target values. The information derived from these simulations provides useful insights for process engineer, and allows network robustness to be integrated as one of the design criteria. Use of Monte Carlo simulation is significant since implementing water network designs in actual industrial contexts may entail difficulties due to noisy or variable mass loads. Identification of sensitive process units allows the network to be redesigned as necessary for increased robustness.

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