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An approach to industrial water conservation – A case study involving two large manufacturing companies based in Australia

Bernard A. Agana [a], Darrell Reeve [b], John D. Orbell [a,b,*]

[a] School of Engineering & Science, Victoria University, PO Box 14428, Melbourne, Victoria 8001, Australia
[b] Institute for Sustainability & Innovation, Victoria University, PO Box 14428, Melbourne, Victoria 8001, Australia

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ABSTRACT

This study presents the application of an integrated water management strategy at two large Australian manufacturing companies that are contrasting in terms of their respective products. The integrated strategy, consisting of water audit, pinch analysis and membrane process application, was deployed in series to systematically identify water conservation opportunities. Initially, a water audit was deployed to completely characterize all water streams found at each production site. This led to the development of a water balance diagram which, together with water test results, served as a basis for subsequent enquiry. After the water audit, commercially available water pinch software was utilized to identify possible water reuse opportunities, some of which were subsequently implemented on site. Finally, utilizing a laboratory-scale test rig, membrane processes such as UF, NF and RO were evaluated for their suitability to treat the various wastewater streams. The membranes tested generally showed good contaminant rejection rates, slow flux decline rates, low energy usage and were well suited for treatment of specific wastewater streams. The synergy between the various components of this strategy has the potential to reduce substantial amounts of Citywater consumption and wastewater discharge across a diverse range of large manufacturing companies.

1. Introduction

Water is a vital commodity in many manufacturing industries. It is used in production processes, process utilities and for a range of other miscellaneous purposes (Dupont and Renzetti, 2001). Production processes utilize water either as a cleaning agent, contaminant diluter, or as part of the final product, whilst process utilities such as cooling towers, boilers and air handling units, utilize water to carry out heat transfer, steam production and to make-up water loss due to evaporation. Employee sanitation and general plant cleaning usually constitute water used for other miscellaneous purposes. Since water is vital to many manufacturing processes and activities, its efficient use should be a priority in order to ensure that water scarcity and increasing water tariffs will have minimal effects on production. Identifying opportunities to improve process water use efficiency usually involves the deployment of different water management strategies such as the water audit, process integration and use of advanced water treatment technologies. Water management strategies provide useful insights into possible process changes that may lead to an increase in water use efficiency and eventually water savings.

A water audit is carried out to measure the quantity and quality of water inputs and outputs within a defined boundary, consisting of a single process or set of processes assumed to be operating at a steady-state (Sturman et al., 2004). One of the most useful outcomes of a water audit is the creation of a water flow diagram – an easy to understand representation of usually complex process systems. A water flow diagram gives an idea of how much water is being used by each process including the volume and quality of the wastewater being generated. It may suggest abnormalities in water usage which cannot be identified during normal operations and can, in itself, facilitate the identification of water saving opportunities within processes (Van der Bruggen and Braeken, 2006).

Process integration is an holistic approach to the analysis, synthesis, and retrofit of process plants (Mann and Liu, 1999). A simple process integration tool widely used for water use optimization is known as water pinch analysis. Water pinch analysis considers water reuse opportunities by carefully analysing the flows and qualities of different streams. Possible water reuse options are identified by matching different "sources" and "sinks".

* Corresponding author. Institute for Sustainability & Innovation, Victoria University, PO Box 14428, Melbourne, Victoria 8001, Australia. Tel.: +61 3 9919 8066.
E-mail address: John.Orbell@vu.edu.au (J.D. Orbell).

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"Sources" are defined as streams coming out of processes carrying, often multiple, contaminants whilst "sinks" are streams going into processes that often have specific water quality requirements (Brauns et al., 2006). Water pinch fundamentals developed by Wang and Smith (1994) and El-Halwagi and Manousiouthakis (1989) have been the basis of many water use optimisation methods deployed in industry in recent times.

The development of water pinch analysis has progressed in two main directions (Manan and Alwi, 2007); namely, graphical methods (El-Halwagi et al., 2003; Feng et al., 2007; Foo et al., 2006; Hallale, 2002; Manan et al., 2004) and mathematical-based methods (Almutlaq et al., 2005; Keckler and Allen, 1998). Both methods have proven to be effective in simultaneously reducing freshwater consumption and wastewater discharge in a number of process industries (Dakwala et al., 2009; Feng et al., 2009, 2006; Thevendiraraj et al., 2003; Tian et al., 2008; Zheng et al., 2006). The choice of which method to use depends on the nature of the problem to be addressed. For example, if one was to tackle a single contaminant problem, a graphical method would be recommended, but where there are multiple contaminants, a mathematical-based method would be a better choice in terms of accuracy. Presently, water pinch analysis of complex water networks can be done using commercially available software packages. Such software packages analyse water networks as steady-state processes and work within the boundaries of sources and sinks (Brauns et al., 2006).

Advanced water treatment technologies such as membrane filtration processes play a major role in the reclamation of water in manufacturing industries worldwide. They have been shown to be applicable to a wide variety of wastewaters generated by industries such as food & beverage, car manufacturing, metal plating, tannery, carpet manufacturing, textile, and glass manufacturing (Bennett; Bes-Piá et al., 2010, 2008; Capar et al., 2006; Chmiel et al., 2003; Holmes, 2002; Kang and Choo, 2003; Qin et al., 2004; Tay and Jeyaseelan, 1995; Van der Bruggen et al., 2004; Wu et al., 2005; Zuo et al., 2008). Since industrial wastewater characteristics are quite diverse, the use of membrane filtration processes for water reclamation is preferred over conventional water treatment technologies since they can deliver more consistent permeate water qualities despite the variations in the quality of feed water (Bennett, 2005). They are also more energy efficient and have smaller footprints compared to conventional water treatment technologies (Zhang et al., 2009). However, the major setback with membrane filtration is fouling – a phenomenon that can greatly affect the performance and life of the membrane (Cheryan, 1998).

Membrane filtration includes four major separation processes; namely, microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) (Chen et al., 2006). In general, MF rejects suspended solids in a size range of 1–0.1 μm, including micro-organisms such as bacteria and protozoa, whilst UF rejects large dissolved molecules and colloidal particles in the size range 0.1–0.01 μm. On the other hand, NF rejects multivalent ions and certain charged particles whilst RO rejects the majority of dissolved constituents in water (Bennett, 2005; Wintgens et al., 2005).

The present work shows the effectiveness of an integrated water management strategy in identifying water conservation opportunities at two large manufacturing companies based in Victoria, Australia. This work may serve as a valuable guide for other manufacturing industries with respect to developing their water management plans.

2. Materials and methods

The integrated water management strategy used in this research, consisting of water audit, process integration and water recycling, is depicted in Fig. 1. To demonstrate the effectiveness of this strategy, two large manufacturing companies based in Victoria, Australia were chosen as case studies. The recruited companies were selected for the following reasons: 1) both use substantial amounts of freshwater in their processes; 2) the manner of freshwater consumption at each company is different; 3) contrasting types of wastewater are generated by each company, and 4) the companies are contrasting in terms of their respective products.

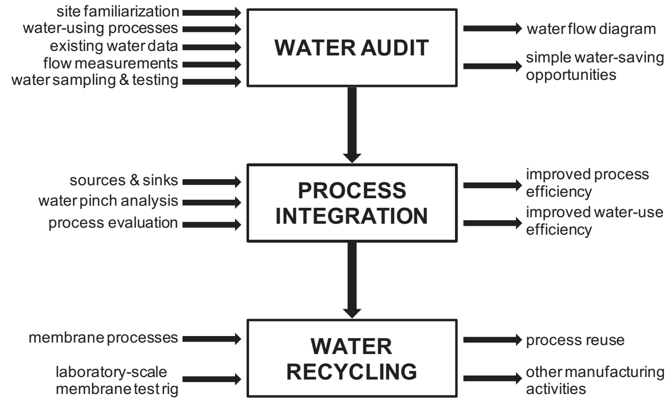

Fig. 1. Schematic diagram of the integrated water management strategy applied at two large manufacturing companies based in Victoria, Australia.

2.1. Case studies

Two large manufacturing companies in the area of Western Melbourne were approached and agreed to be case studies for this program. Due to confidentiality agreements, their names will not be divulged and instead they will just be referred to in this paper as Companies A & B. Company A is an automobile manufacturer and Company B is a major producer of non-alcoholic drinks and cordials. Since both companies are within the same area, they are subjected to similar water tariffs and water restrictions. Likewise, both companies have tradewaste discharge agreements with the same local water retailer, who was also a partner on the project.

2.2. Water audit

Components of the water audit deployed for both companies include site familiarization, classification of water-using processes, analysis of existing water data, flow measurements, and water sampling and testing. Site familiarizations were undertaken prior to commencing actual flow measurements and water sampling to ensure that issues relating to occupational health and safety (OH&S) were addressed in advance. Meanwhile, the classification of all water-using processes facilitated the systematic development of the water flow diagram. These were classified as either mass-transfer-based (MTB) or non-mass-transfer-based (NMTB) processes. MTB processes utilize water as a mass separating agent (e.g. product cleaning), while NMTB processes may utilize water as a cooling or heating medium (e.g. cooling towers, boilers, etc.), or a raw material that eventually becomes part of a product (e.g. softdrinks production) (Manan and Alwi, 2007). After site familiarization, existing water data obtained from both companies were analysed. These data provided insights on the quantity and quality of water consumed and wastewater generated. These were subsequently used as guidelines in flow measurements and wastewater sampling.

Flow measurements were carried out using multiple portable clamp-on ultrasonic flow meters, which were installed at different locations within the manufacturing site and which were programmed to log flow rates and accumulated volumes from periods ranging from days to weeks. The logged data were downloaded and were graphed and analysed for trends and irregularities.

Wastewater samples were taken from strategic points within the manufacturing site to ensure that every type of wastewater stream is represented in the study. Samples were collected in plastic and glass containers provided by a contracted analysis laboratory and were tested for a range of water quality parameters including, pH, conductivity, Total Dissolved Solids (TDS), Suspended Solids (SS), Oil & Grease (O&G), Chemical Oxygen Demand (COD) and various metals. Water sampling was carried out in that part of the production week that captured the worst case scenario in terms of contamination levels.

2.3. Process integration

The process integration method used in this study consists of water pinch analysis and process evaluation. Water pinch analysis was carried out using commercially available software known as WaterTarget™. The software theoretically identifies water reuse opportunities by matching the different flow rates and water qualities of sources and sinks. In this case, the sources and sinks used in the analysis were obtained from the water audit. On the other hand, process evaluation involves the use of fundamental engineering concepts to assess the applicability of the water pinch results on actual plant conditions. Process evaluations were done in conjunction with the management team and process engineers of both companies.

2.4. Water recycling

The regeneration potential of selected wastewater streams generated at each company was assessed via laboratory-scale trials on a test rig, Fig. 2, using membrane filtration processes such as UF, NF and RO. Membrane materials used in these experiments include ceramic (UF) and flat sheet polymeric membranes (UF/NF/RO). UF membranes were evaluated based on fouling rates and ability to reject suspended particles in the wastewater. Particle rejection rates for the UF membranes were estimated using turbidity measurements. Similarly, NF and RO membranes were also evaluated based on fouling rates and ability to reject certain contaminants such as ions, COD, metals, and TDS. Fouling rates for all the membranes used were measured in terms of flux decline while contaminant reduction/rejection rates (C_R) were calculated using Eq. (1).

$$C_R = (C_F - C_P)/C_F \times 100\% \quad (1)$$

where C_F is the feed contaminant concentration and C_P is the permeate contaminant concentration.

The specifications of the different membranes used in the trials are shown in Table 1. Ceramic membranes were chemically cleaned after each trial to facilitate reuse while used flat sheet polymeric membranes were replaced with new ones at the start of each trial.

3. Results and discussion

A number of irregularities in water use, mostly associated with employees' work practices, were detected during the water audits. These irregularities emanate from work practices performed during manual addition of freshwater into processes, equipment cleaning and general plant cleaning. Since the irregularities in water use were mostly due to employees' work practices, this is best resolved through direct management intervention. This would include the provision of training and seminars aimed at changing employees' perception on water use.

3.1. Water uses

The main source of water used at the production sites of both companies is Citywater – i.e. freshwater supplied by the local water retailer. The average water qualities of the Citywater used at each site is shown in Table 2.

Rainwater is also used at both sites but is only available during certain periods of the year and therefore is not considered a reliable source. The different uses of the Citywater at the production sites of each company are shown in Fig. 3a and b. These water uses can be summarized as follows.

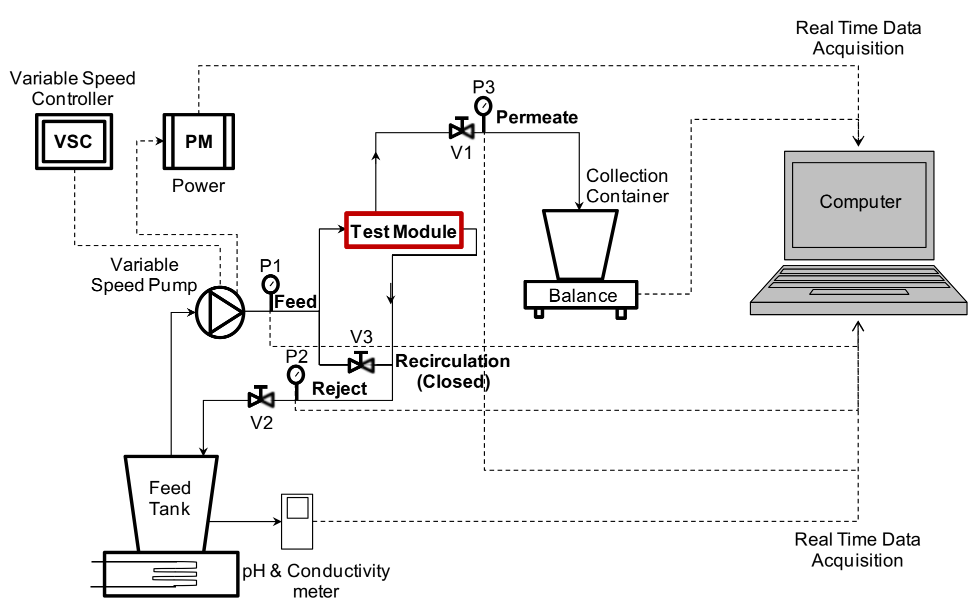

Fig. 2. Schematic diagram of the laboratory-scale membrane test rig used in the experiments. Solid lines represent water flow while broken lines represent real time data acquisition. *P*1 – feed pressure; *P*2 – concentrate pressure; *P*3 – permeate pressure; *V*1 – permeate valve; *V*2 – concentrate valve; *V*3 – recirculation valve.

Table 1
Specifications of different membranes used in the trials. The average NaCl rejection rate for the AK (RO) membrane is 99.0%. TFC – thin film composite; PVDF – polyvinylidine-difluoride; PAN – polyacrylonitrile; ZrO_2 – zirconium dioxide; TiO_2 – titanium dioxide.

Membrane	Code	Type	Material	Pore Ø (nm)	MWCO (kD)	Area (m^2)	Active layer	Supplier
UF	T1-70	Tube	Ceramic	50	–	0.005	ZrO_2	Pall Corp
	T1-70	Tube	Ceramic	5	–	0.005	TiO_2	Pall Corp
	JW	Sheet	PVDF	3	30	0.0042	–	GE
NF	DL	Sheet	TFC	–	0.15–0.30	0.0042	–	GE
RO	AK	Sheet	TFC	–	–	0.0042	–	GE

3.1.1. Company A

- Of the total Citywater supplied, 19.1% is treated via deionization (DI) system while 5.0% is treated via a reverse osmosis (RO) system. DI and RO water are mainly used for product washing/rinsing at the final pretreatment and post-treatment stages. Likewise both types of treated water are also used to replenish the electrocoat bath. Approximately 15.2% of the total Citywater supplied is used for product washing/rinsing at the initial pretreatment and post-treatment stages while 26.1% is used for personal sanitation and miscellaneous plant cleaning. A small portion (0.6%) of the total Citywater supplied is also used to replenish the electrocoat bath. The remaining 34.0% of the total Citywater supplied is used as either feed or make-up water to process utilities such as air handling units, boilers, cooling towers, pumps, and sludge pools.
- MTB processes account for 67.7% of the total Citywater consumption while NMTB processes account for 32.3% of the total Citywater consumption.
- The shop with the highest water consumption is paint shop – utilizing 49.0% of the total Citywater supplied.

3.1.2. Company B

- Approximately 66.3% of the total Citywater supplied is treated via a treatment system consisting of clarifier, sand filter, carbon filter, bag filter, and UV sterilizer. The treated water is mainly used for clean-in-place (CIP) systems, product mix, syrup mix, and sterilizing carbon filters. Roughly 13.6% of the total Citywater supplied is used for washing/rinsing product containers while 9.6% is used for personal sanitation and miscellaneous plant cleaning. The remaining 10.5% of the total Citywater supplied is used as either feed or make-up water to process utilities such as boilers, cooling towers, coolers/warmers, wet lube conveyors, and vacuum pumps.
- MTB processes account for 40.3% of total Citywater consumption while NMTB processes account for 59.7% of total Citywater consumption.
- Approximately 48.7% of the total Citywater supplied is used for beverage production.

3.2. Wastewater characteristics

As mentioned previously, the wastewater streams generated at each company's production site differ markedly from each other. Contaminants generally present in Company A's wastewater streams include paint particles and metals while cleaning chemicals and product components are the contaminants generally present at Company B's wastewater streams. The average water qualities of these streams are described as follows.

Table 2
Average water qualities of Citywater supplied to companies A and B. TDS – total dissolved solids; SS – suspended solids; O&G – oil and grease; COD – chemical oxygen demand.

Category	pH	TDS (mg/L)	Conductivity (μS/cm)	SS (mg/L)	O&G (mg/L)	COD (mg/L)
Citywater to A	7.3	79	129	<1	<5	<5
Citywater to B	7.2	36	83	<1	<5	<5

3.2.1. Company A

Approximately 49% of the total Citywater supplied ends up as Tradewaste while the remainder is either discharged directly into the sewer or is lost due to evaporation. Wastewater streams generated at the manufacturing site are segregated upon collection and are classified into three categories namely, oily, metals and general streams (as shown in Fig. 3a). The segregation of wastewater streams facilitates the treatment of specific contaminants. For example, oil & grease and electrodeposition (ED) paint emulsions are removed from the oily stream prior to discharge. Likewise, metals such as nickel (Ni), zinc (Zn) and manganese (Mn) are also removed from the metals stream prior to discharge. All streams are mixed together after undergoing the relevant treatment and eventually discharged as Tradewaste. Table 3 presents the average water qualities of the different wastewater streams found in company A's manufacturing site. Only the main parameters limiting water reuse are shown.

3.2.2. Company B

Of the total amount of Citywater used on production site, approximately 53.7% ends up as wastewater while the remaining 46.3% is either mixed with the final products or is lost due to evaporation. A substantial amount of the total wastewater can be traced to discharges generated by process utilities such as boilers, CIP systems, cooling towers, wet lube conveyors, coolers/warmers, vacuum pumps, and washer/rinsers. Contaminants commonly found on Company B's wastewater streams include cleaning chemicals, product mixes and concentrates, and sugars. All wastewater streams are mixed together and discharged as Tradewaste after the pH level has been adjusted. The average water quality of Tradewaste discharge is shown in Table 4. Similar to Company A, only the main parameters limiting water reuse are shown.

3.3. Water pinch and process evaluation

Commercially available water pinch software (Brauns et al., 2008) called WaterTarget™ was used in analysing Company A and B's water networks under steady-state conditions. The mass balance equations used in analysing the water-using processes found in these networks are as follows:

$$\sum \text{Mass flow}_{IN} = \sum \text{Mass flow}_{OUT} \tag{2}$$

$$\sum \text{Mass flow}_{IN} = \sum \text{Mass flow}_{OUT} + \sum \text{Evaporative losses} + \sum \text{Misc. Losses} \tag{3}$$

Eq. (2) assumes that water losses are negligible and best represents MTB processes. Eq. (3) suggests that there are losses to

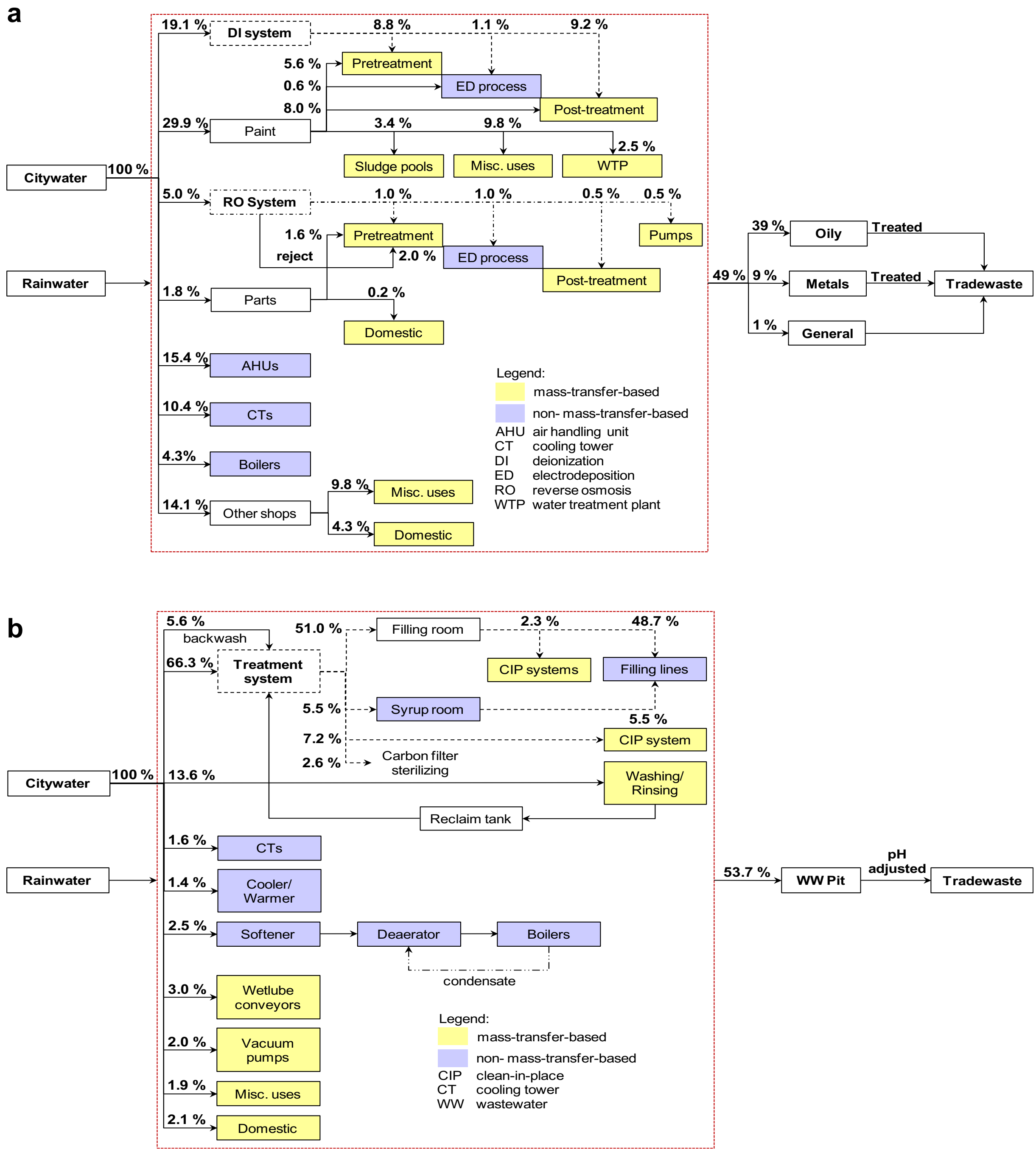

Fig. 3. Water flow diagrams for (a) Company A and; (b) Company B.

be accounted for such as evaporative and other miscellaneous losses. This mass balance equation best represents NMTB processes. Since the mass balance equations are steady-state representation of process types, average steady flows were used (Brauns et al., 2008). These averages represented 2–4 days of real time data logging.

The identified sources and sinks together with their mass flow rates and water quality data were encoded into the water pinch

Table 3
Average water qualities of different wastewater streams found at company A's manufacturing site. SS – suspended solids; O&G – oil and grease; COD – chemical oxygen demand.

Category	pH	Conductivity (μS/cm)	SS (mg/L)	O&G (mg/L)	COD (mg/L)
Oily stream	8.8	545	130	45	575
Metals stream	3.7	1595	188	21	250
General stream	6.7	187	7	<5	14
Tradewaste	8.4	1555	28	7	280

Table 4
Average water quality of tradewaste discharge at company B's production site. TDS – total suspended solids; SS – suspended solids; O&G – oil and grease; COD – chemical oxygen demand.

Category	pH	TDS (mg/L)	SS (mg/L)	O&G (mg/L)	COD (mg/L)
Tradewaste	8.3	2369	41	9	2950

software prior to starting the analysis. Water pinch analysis for Company A was focused on shops with the most number of water-using processes (paint and parts) while water pinch analysis for Company B focused on the whole production site. The results of the analyses are as follows.

3.3.1. Company A

Results of the water pinch analysis for Company A identified three main processes where possible water saving opportunities can be achieved. These processes include air handling units (AHUs), car body preparation and car parts preparation – as highlighted in Fig. 4.

3.3.1.1. Air handling units (AHUs). The AHUs for Company A's manufacturing site are mainly used to condition the incoming air supply of the painting booths. The main users of Citywater in the AHUs are the humidifiers. Citywater is continuously supplied to the humidifiers to offset evaporation and bleed-off losses. Evaporation loss occurs during the humidification process while bleed-off loss takes place continuously in order to maintain the quality of the water being recirculated in the system. Maintaining the correct quality of water recirculated in the system prevents the build up of solids and scale on the humidifier pads.

A portion of the bleed-off volume is currently being utilized as make-up water for the sludge pools. Bleed-off that goes into the sludge pools is controlled via solenoid valves. Once the level of the water in the sludge pools fall under the control level limits, the solenoid valves open for a specific length of time and shut off once the Citywater supply comes on- line. The moment the solenoid valves shut off, all bleed-off is diverted back into the drain. The current set-up decreases the Citywater consumption but further reuse of the bleed-off is still possible.

Further use of the bleed-off was trialled on two sludge pools. The trial lasted for more than a month. Citywater usage was recorded prior to changes in control settings. The changes involved delaying Citywater fill by 30 s in order to utilize more AHUs' bleed-off and setting the Citywater fill time to 60 s. Prior to control modifications, the average Citywater use for the two sludge pools was 28 tonnes/day. After the modifications, Citywater use for the two sludge pools decreased to 15 tonnes/day. This translated to approximately 13 tonnes/day of Citywater savings.

It is also worth mentioning that reuse of all the bleed-off into the sludge pools may not be viable because this may increase the conductivity level of the pools. Therefore, at any time, only an optimum volume of bleed-off should be diverted into the sludge pools. This optimum volume should not increase the conductivity level above the specified operating limit.

3.3.1.2. Car body preparation. Car body preparation prior to electrodeposition (ED) painting involves a number of pretreatment processes. Pretreatment increases a car body's resistance to corrosion and facilitates better adhesion of the electrodeposition paint. It is commonly made up of different stages which include degreasing, rinsing, phosphating, and deionized (DI) water rinsing (Gehmecker, 2007). Electrodeposition painting is a process commonly used in car manufacturing to render car bodies virtually rustproof. Deposition of electrocoat paint is achieved by immersing car bodies into an electrocoat tank connected to a rectifier. A voltage of more than 300 V is then applied to the electrodes in the tank to facilitate the diffusion and migration of dispersed electrocoat paint particles onto the car body (Streitberger, 2007). After ED painting, car bodies are subjected to series of post-treatment rinses utilizing Citywater, ultrafiltration water and DI water. Rinsing of car bodies after ED painting is primarily carried out to remove non-adhered electrocoat paint.

Fig. 5 shows the water flow diagram at company A's car body preparation section. The types of wastewater generated from this section are considered to be the "oily and metals" streams. These streams are collected separately and treated prior to discharge. The main water quality parameters limiting water reuse in this section include conductivity, suspended solids (SS) and oil & grease (O&G). Each of the water quality parameters mentioned are carefully monitored because they can affect ED paint quality. For example, oil contamination in the ED bath can increase the risk of craters being produced in the paint film. Similarly, tiny particles such as welding pearls not completely removed from car bodies can lead to paint defects like paint splits or rust (Streitberger, 2007).

An initial water pinch analysis revealed that direct water reuse within the current car body preparation section was not possible due to the high level of contamination in the wastewater streams. For example, DI water fed to stage 12 cascades down to stages 11 to 9 (Fig. 5) and eventually gets discharged down the drain from stage

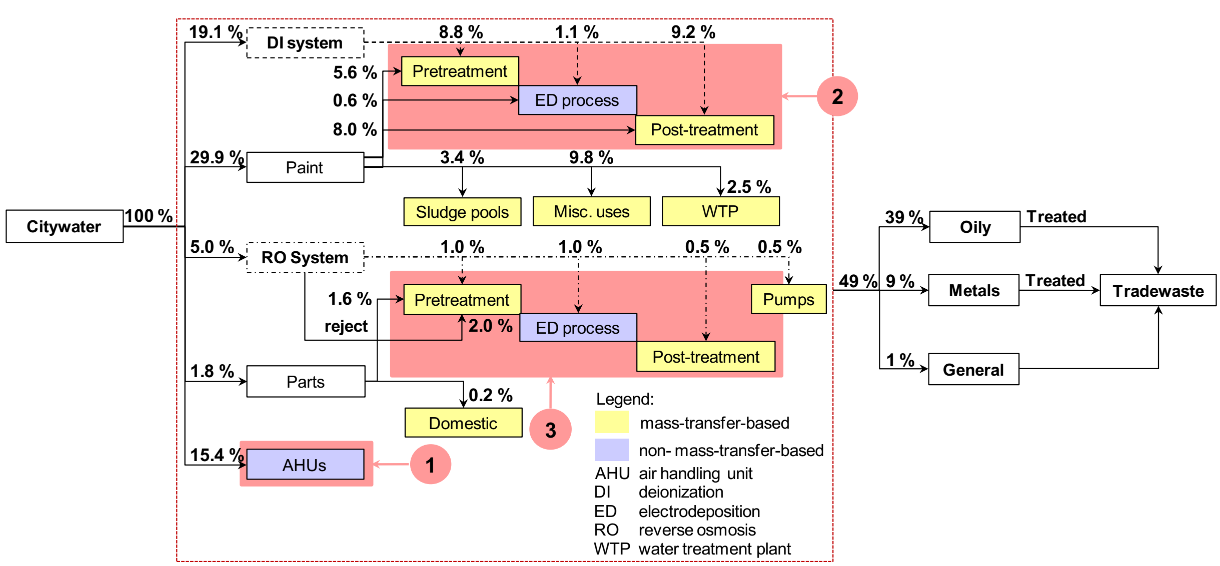

Fig. 4. Water flow diagram of shops with the most number of water-using processes. Processes identified as having the potential for water saving opportunities are highlighted in light red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

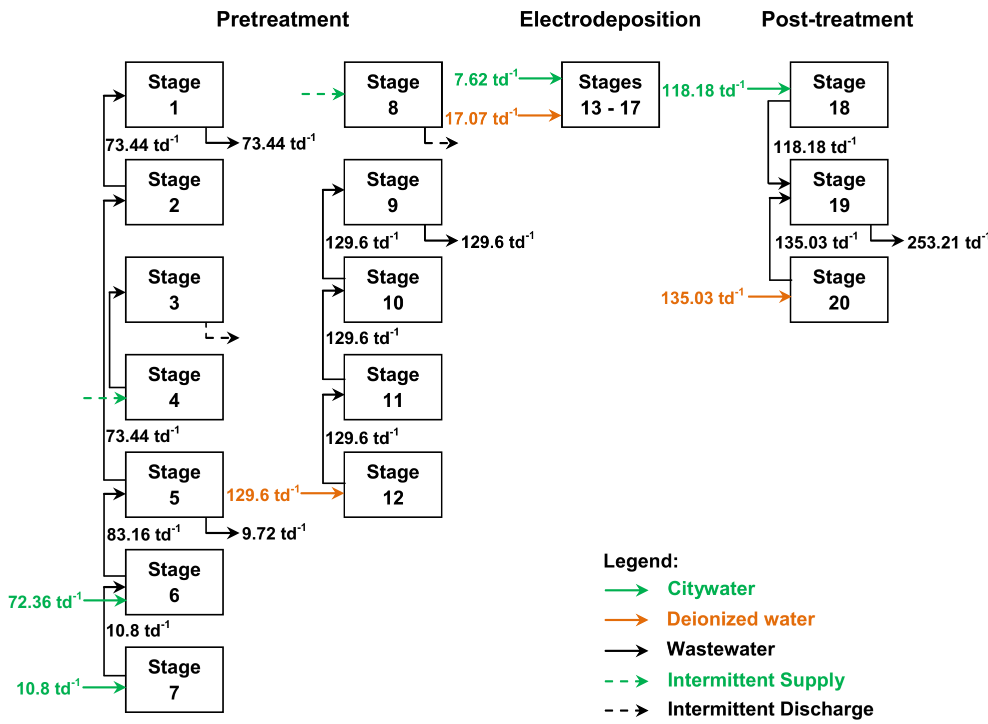

Fig. 5. Current water flow diagram for Company A's car body preparation section. The amount of Citywater used and wastewater discharged is given in tonnes per day.

9. The contamination level changes within each stage and is highest upon discharge. Although this was generally the case, water test results showed that wastewater generated at stage 19 (Fig. 5) has the best water quality among the different wastewater streams found at the car body preparation section (Table 5). Obviously, the removal of suspended solids (mainly paint particles) as well as O&G will facilitate the reuse of stage 19's wastewater into other stages.

A 50 nm ceramic ultrafiltration membrane was tested on Stage 19's wastewater (Agana et al., 2011). The results of this trial showed that approximately 99.5% of suspended paint particles can be rejected by the ceramic membrane. Likewise, a 100% rejection of O&G was also recorded. Since it was verified that the 50 nm ceramic ultrafiltration membrane is capable of removing specific contaminants of concern, a re-run of the water pinch analysis was done. This re-run considered the installation of a ceramic membrane at stage 19 to reclaim the wastewater generated. Suspended particles and O&G rejection rates used for this ceramic membrane were similar to the actual rates obtained during testing. The result of the new water pinch analysis for the car body preparation section is shown in Fig. 6.

With the proposed new water flow diagram, the Citywater supply into stages 6 and 7 can be completely replaced by ceramic membrane filtrate – as shown in Fig. 6 – representing a savings of 83.16 tonnes/day.

Table 5
Average water qualities of wastewater streams generated at company A's car body preparation section. SS – suspended solids; O&G – oil and grease; COD – chemical oxygen demand.

Wastewater	pH	Conductivity (μS/cm)	SS (mg/L)	O&G (mg/L)
Stage 1	10.4	6160	706	342
Stage 3	11.1	16410	74	62
Stage 5	9.94	849	52	6
Stage 9	3.58	1280	46	9
Stage 19	6.7	56.2	12	10

3.3.1.3. Car parts preparation. The car parts preparation section found at the parts shop is similar in operation to the car body preparation section at the paint shop. Main processes found at this section include pretreatment, ED and post-treatment. The current water flow diagram for this section is shown in Fig. 7.

The largest user of water in the car parts section is Stage 2 (Fig. 7). It utilizes an average of 20.6 tonnes/day of Citywater and 24.4 tonnes/day of RO concentrate as make-up water. The existing overflow rate for this stage is set at 45 tonnes/day to maintain a bath alkalinity concentration of 0.3 ppm. Water pinch analysis for Stage 2 suggests that by maintaining a higher bath alkalinity level, less make-up water will be needed by the process because the overflow rate can be decreased. A discussion with Company A's subcontractor confirmed that the bath at Stage 2 can operate within an alkalinity range of 0–1 ppm. Although the bath alkalinity can go up to 1 ppm, actual changes must be within the range of 0–0.8 ppm to have a 20% safety factor. The 20% safety factor is a standard operating buffer incorporated by the company in every design project they undertake.

After consulting with appropriate staff at the car parts preparation section, an actual trial at Stage 2 was commenced. The overflow rate at Stage 2 was initially reduced to 28.0 tonnes/day and the alkalinity reading increased to 0.7 ppm. A further reduction of the overflow rate to 25.0 tonnes/day resulted in the same alkalinity reading of 0.7 ppm. At this point, the adjustment was stopped since further reducing the overflow rate will only result in an alkalinity level equal to or above the maximum operating value identified. With the latest overflow rate, Stage 2 presently utilizes approximately 24.4 tonnes/day of RO concentrate and 0.6 tonnes/day of Citywater – as shown in Fig. 8. The adjustment of the overflow rate at Stage 2 resulted in a Citywater saving of approximately 20.0 tonnes/day.

3.3.2. Company B

Company B's current water flow diagram with actual flow measurements is shown in Fig. 9a. The results from the water pinch

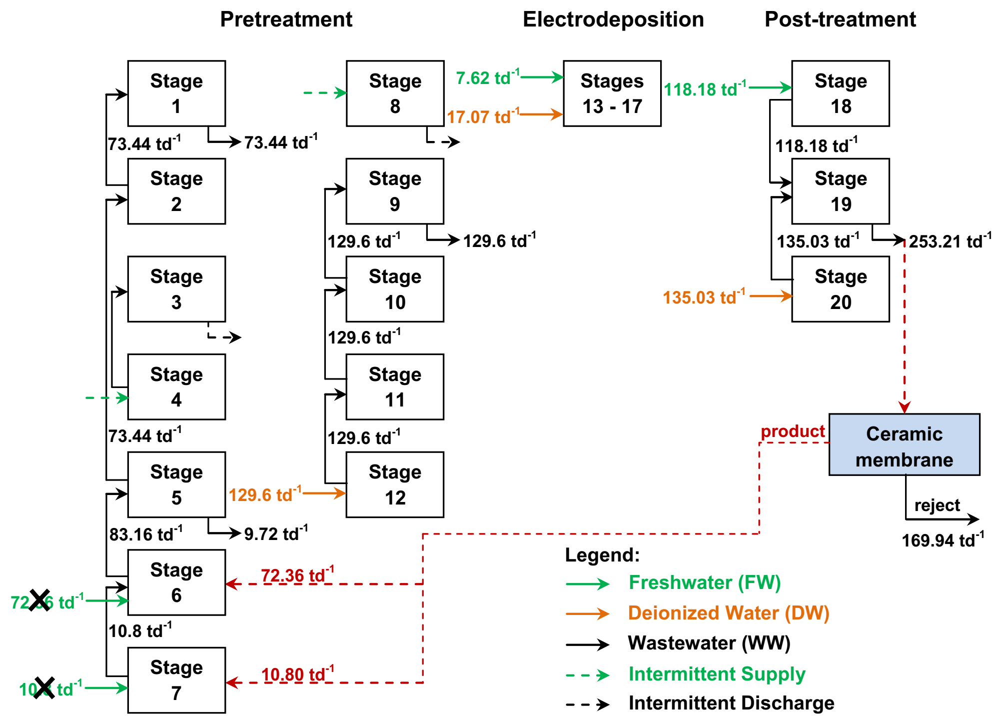

Fig. 6. Proposed new water flow diagram for car body preparation section. The amount of Citywater used and wastewater discharged is given in tonnes per day.

analysis suggest that a number of wastewater streams generated by some process utilities can be collected at the reclaim tank (Fig. 9b, red broken lines) and re-supplied back into production processes via the water treatment system. Sources of these streams include vacuum pumps, boilers and washer/rinsers. These wastewater streams have been found to have equal or better water quality compared to the current water collected in the reclaim tank – as shown (in bold) in Table 6.

The wastewater streams identified above as having the potential for reuse need only minimal treatment prior to redirection into the reclaim tank. For example, boiler condensate must pass through a heat exchanger before being collected in order to bring down the temperature to ambient level. By reclaiming the wastewater streams generated from the processes mentioned above, a Citywater saving of 80.8 tonnes/day can be achieved.

Other wastewater streams in Company B's production site are identified as needing some form of major treatment before they can be reused in the production processes. The choice of treatment can be addressed via the experimental membrane test rig. The experimental test rig evaluates the performance of different low energy membranes on specific wastewater streams generated at both companies. Results from the evaluation provide insights on the

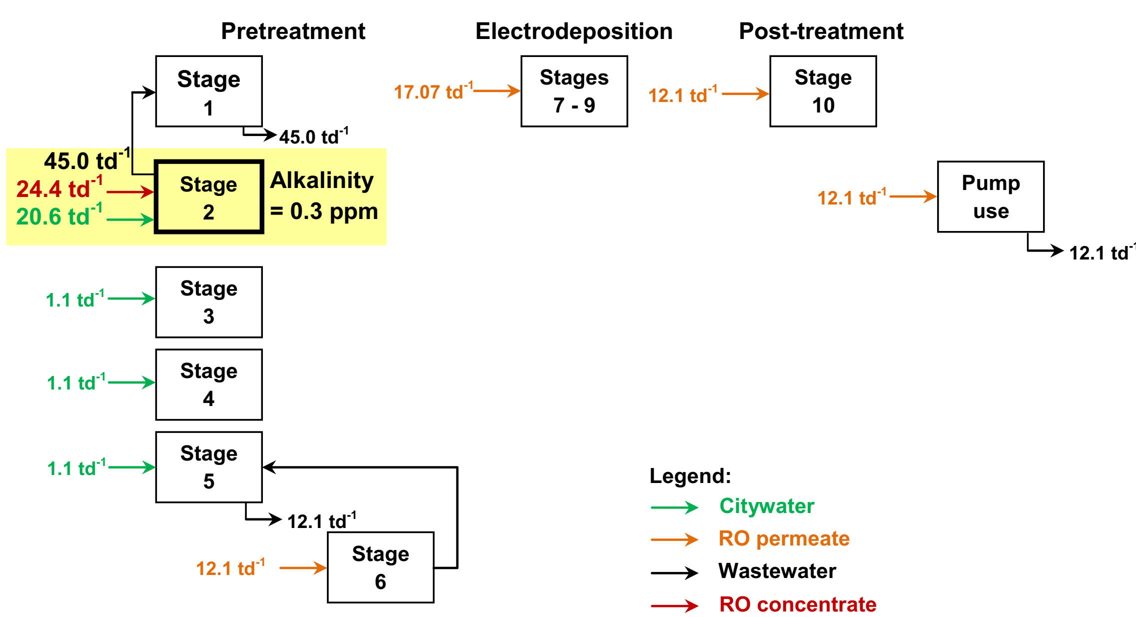

Fig. 7. Current water flow diagram for company A's car parts preparation section. The amount of Citywater used and wastewater discharged is given in tonnes per day.

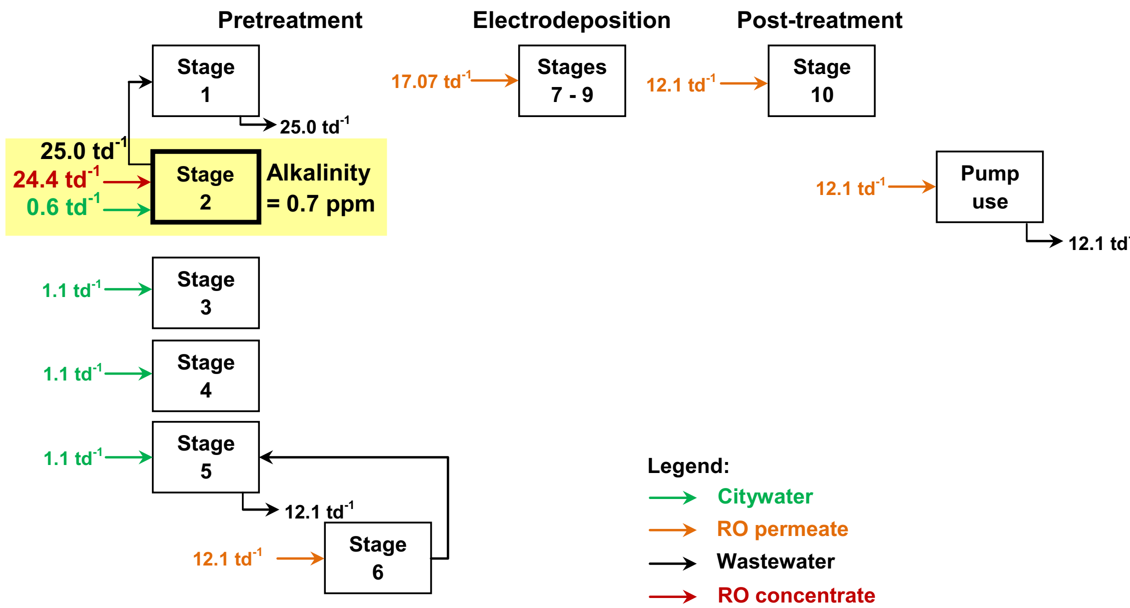

Fig. 8. Proposed new water flow diagram for car parts preparation area. The amount of Citywater used and wastewater discharged is given in tonnes per day.

applicability of the different membranes tested to the reclamation of specific wastewater streams.

3.4. Water recycling

The results of the water audit and the pinch analysis for both companies suggest that the biggest opportunity for water reuse comes from the most contaminated wastewater streams – although this is not necessarily a general rule. Here, these wastewater streams happen to represent the largest portion of the total wastewater volume generated at each company as shown in Fig. 10A and B. The reclamation and reuse of these streams will necessarily involve the introduction of some form of water treatment equipment capable of efficiently removing water contaminants in a cost effective manner.

Not unexpectedly perhaps, the wastewater treatment approaches that are best suited to each of the contrasting manufacturers differ. Overall, for Company A, a distributed effluent treatment approach is found to be appropriate, since the wastewater streams that are generated by the different processes are segregated upon collection. The segregation of streams facilitates the installation of specific water treatment equipment suitable for the type of contaminants that are present in the wastewater. However, a distributed effluent approach is not appropriate for company B due to the lack of existing infrastructure that would enable the wastewater streams to be collected separately. All wastewater streams at Company B's production site are mixed in drains and end up at a single wastewater collection pit. With Company B's current set-up, the appropriate option for water reclamation is to treat the mixed stream – that is currently discharged as Tradewaste.

Two stages of water treatment were investigated during this study – namely, pretreatment and main treatment. Pretreatment of wastewater is a very important step to lengthen the operating life of main treatment systems such as RO and NF. An established wastewater pretreatment technology commonly used in industrial applications is UF. It has been reported to be effective in removing suspended solids and emulsified oils present in industrial wastewater (Karakulski and Morawski, 2000; Norouzbahari et al., 2009; Zhang et al., 2008). Likewise, its filtrate water quality has also been shown to meet RO and NF feed water quality requirements (Fersi and Dhahbi, 2008; Qin et al., 2003; Uzal et al., 2009; Zhang et al., 2008). Meanwhile, the main treatment stage composed of either RO or NF will remove the dissolved organic and inorganic contaminants present in the wastewater.

Specifically, for this study, a UF/RO combination was tested on the oily and Tradewaste streams generated at Companies A and B respectively while a UF/NF combination was tested on Company A's metals stream. A schematic diagram of the proposed treatment processes for each stream is shown in Fig. 11.

Table 6
Average water qualities of wastewater generated by process utilities at Company B's production site. TDS – total suspended solids; SS – for suspended solids; O&G – oil and grease; COD – chemical oxygen demand.

Process utilities	pH	TDS (mg/L)	SS (mg/L)	O&G (mg/L)	COD (mg/L)
Reclaim tank	6.4	92.0	120.0	7.0	81.0
Boiler condensate	**7.1**	**60**	**3.0**	**<5**	**9.0**
Conveyor	4.4	550.0	290.0	7.0	1800.0
Vacuum pumps	**6.5**	**46.0**	**<2**	**<5**	**68.0**
Washer/rinsers	**6.0**	**84.0**	**2.0**	**<5**	**11.0**

3.4.1. Pretreatment

The first step in evaluating a candidate UF membrane for pretreatment of a particular waste water stream involves characterizing the particle size distribution for the stream. Thus, prior to test rig experiments, the particle size distributions of three selected wastewater streams were determined, these are described in Fig. 12.

Using the above information, candidate UF membranes were evaluated using the test rig. Particle rejection rates, estimated using turbidity measurements of feed and filtrate water (Section 2.4), are shown in Table 7.

Aside from turbidity, other water parameters such as total organic carbon (TOC) and O&G were also reduced by the UF membranes tested. For the filtrate collected in all of these UF experiments, O&G was undetectable and an average of 22% TOC reduction was recorded.

An important part of the pretreatment membrane evaluation also involves a determination of the fouling characteristics.

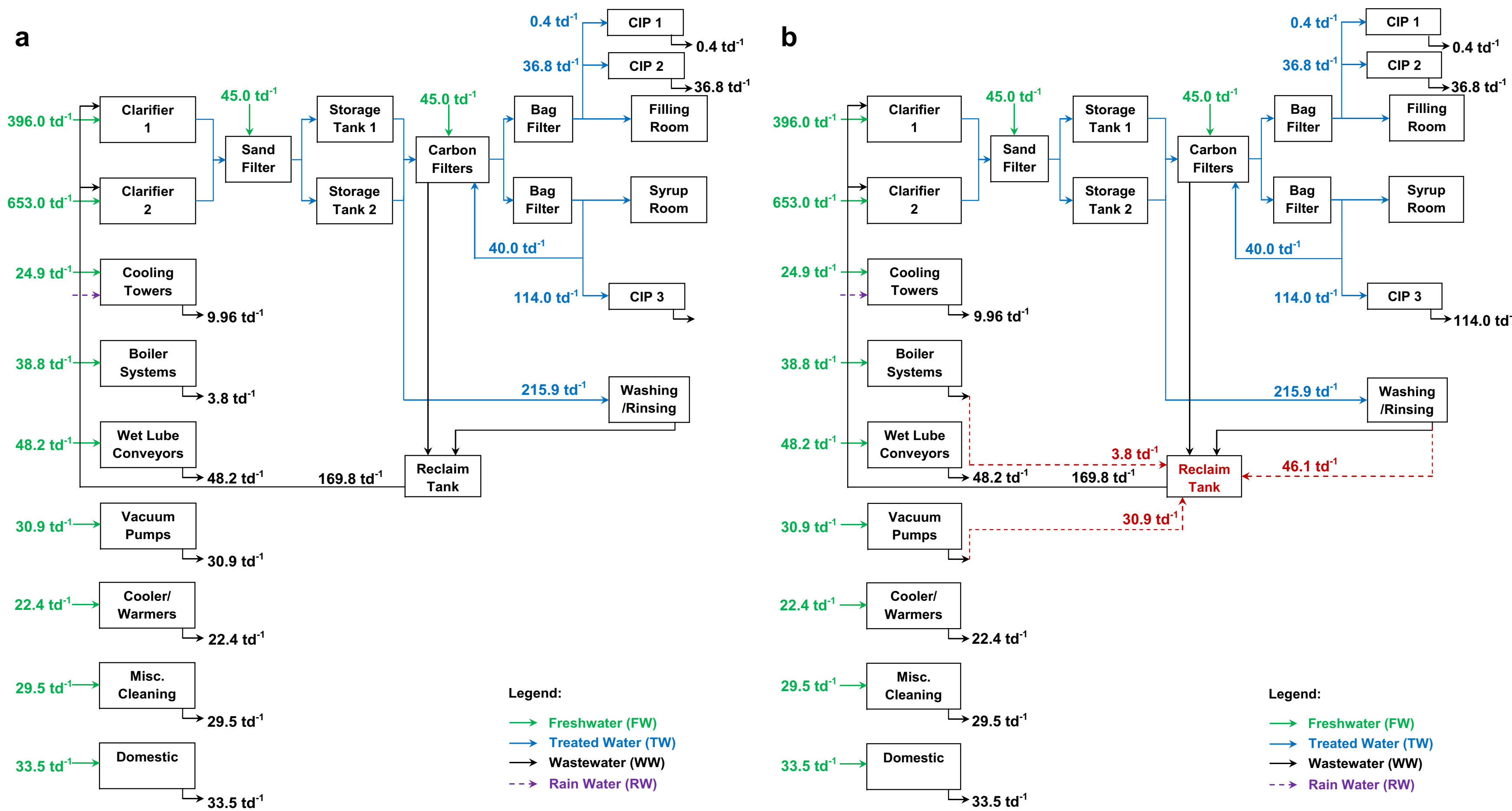

Fig. 9. Company B's (a) current water flow diagram and; (b) proposed new water flow diagram.

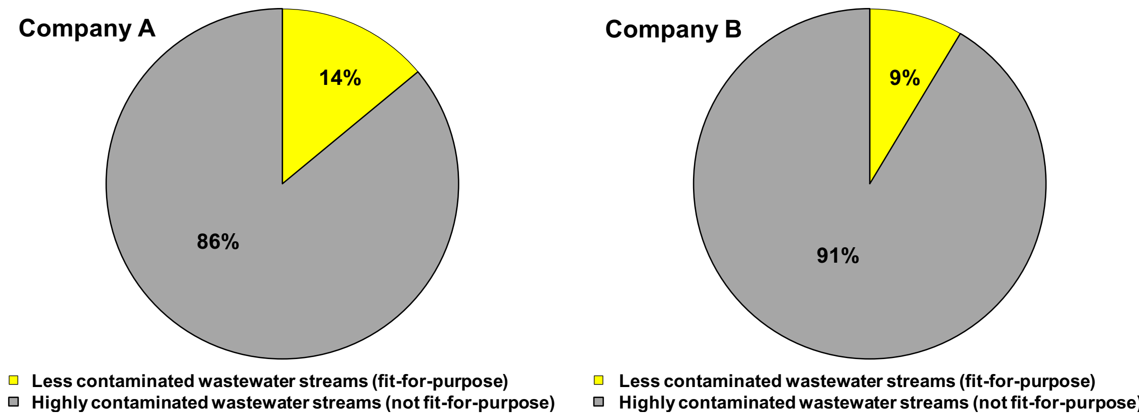

Fig. 10. General categories of wastewater generated at the two manufacturing companies studied based on degree of contamination.

Fig. 13a–c shows the measured permeate fluxes of the UF membranes tested for the specific wastewater streams they were applied into. Membrane fouling due to cake layer formation was controlled by increasing crossflow velocity (CFV). The increase in CFV resulted in a more a turbulent flow which subsequently weakened the effect of concentration polarization (Baker et al., 1985) resulting in slower fouling and relatively higher permeate fluxes (Agana et al., 2011).

Maintaining a high CFV translates to more energy consumption (Agana et al., 2011; Waeger et al., 2010) – as demonstrated on the test rig, Table 8. The increase in energy consumption can be attributed to the pump motor exerting more power to deliver the desired CFV and will be significant for systems requiring larger pumps. However, other factors such as a decrease in membrane cleaning frequency, an increase in membrane life and an increase in membrane flux may outweigh the energy cost associated with maintaining a high CFV.

3.4.2. Main treatment

The main treatment system will treat the dissolved constituents for the different wastewater streams. For example, using the test rig, the NF membrane shown in Table 1 was tested on Company A's metals stream to evaluate conductivity reduction, as well as the rejection of the predominant metal contaminants, including Mn, Ni and Zn. Table 9 shows the performance of the NF membrane in terms of conductivity reduction and specific metal rejection at different TMPs.

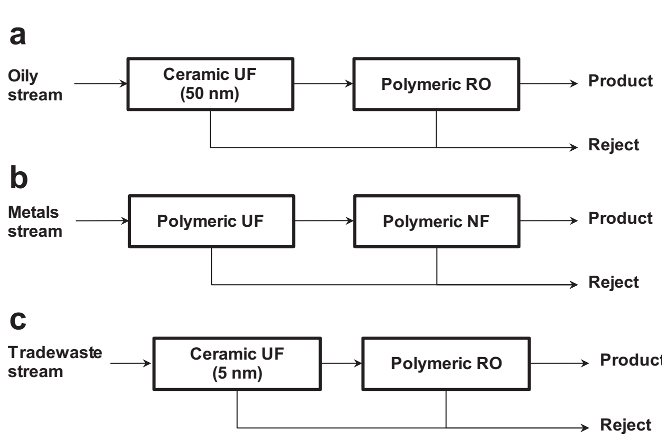

Fig. 11. Schematic diagram of the proposed treatment processes for (a) Company A's oily stream; (b) Company A's metals stream and; (c) Company B's Tradewaste stream.

As shown in Table 9, conductivity and specific metal contaminants measured in the filtrate does not vary greatly at different applied TMPs. Since this is the case, a relatively lower operating pressure for the NF membrane is the most viable option. The use of a lower operating pressure results in reduced energy usage as well as slower membrane fouling – as shown in Fig. 14a and b.

The low energy RO membrane shown in Table 1 was tested on the oily and Tradewaste streams found at Companies A and B respectively. The RO membrane was evaluated based on its ability to reduce conductivity, COD and TDS. Specifically, conductivity and COD were measured for the oily stream while COD and TDS were measured for the Tradewaste stream. Table 10 shows the performance of the RO membrane on the wastewater streams mentioned above.

The RO membrane used in the tests was very effective in reducing conductivity, COD and TDS. Reduction rates for all wastewater parameters in focus were above 91% – as shown in Table 10. It was also observed that permeate fluxes of the RO membrane shown in Fig. 15a exhibited gradual permeate flux decline rates for both wastewater streams used. Likewise, energy usage (Fig. 15b) of the RO membrane is comparable to the energy

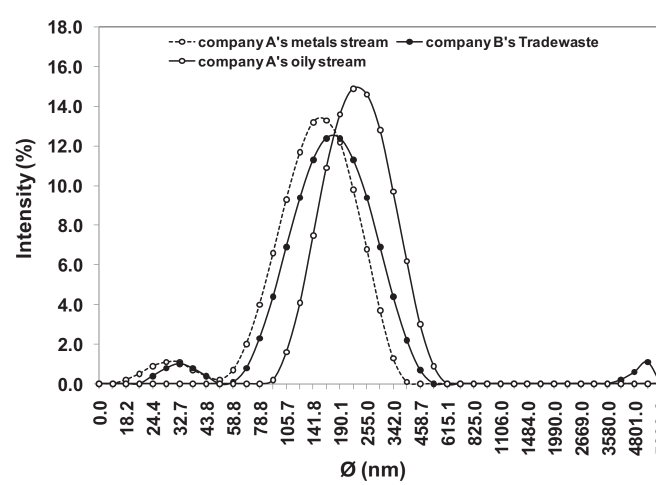

Fig. 12. Particle size distributions for different wastewater streams found at Company A and B's production sites. Company A's oily wastewater stream has particle sizes in the range of 90–532 nm with a mean diameter of 245 nm while its metals wastewater stream has particle sizes in the range of 18–397 nm with a mean diameter of 134 nm. Company B's Tradewaste stream has particle sizes in the range of 28–5560 nm with a mean diameter of 184 nm.

Table 7
Turbidity rejection rates of UF membranes used. Fw – feedwater; Fl – filtrate; T_R – turbidity rejection rate. Turbidity unit used is Nephelometric Turbidity Unit, NTU.

Wastewater stream	Co.	UF membranes (see Table 1)								
		JW (PVDF)			Ceramic 50 nm			Ceramic 5 nm		
		Fw	Fl	T_R (%)	Fw	Fl	T_R (%)	Fw	Fl	T_R (%)
Oily	A	–	–	–	294	0.5	99.8	–	–	–
Metals	A	43	0.3	99.3	–	–	–	–	–	–
Tradewaste	B	–	–	–	–	–	–	30.9	0.3	99.0

Table 8
Energy consumptions of feed pumps used as a function of CFVs.

Wastewater stream	UF membrane type used	Feed pump (kW)	CFV (m s^{-1})	Energy consumption (kWh)
Oily	50 nm ceramic	0.56	2.4	0.142
			2.8	0.155
			3.2	0.162
Metals	JW (PVDF-UF)	0.37	2.5	0.052
			3.1	0.064
			3.6	0.074
Tradewaste	5 nm ceramic	0.37	2.5	0.066
			3.1	0.074
			3.6	0.085

usage (Fig. 14a) of the NF membrane used in this study. The low energy usage of the RO membrane can be attributed to its inherent characteristic of being a low-pressure membrane.

3.5. Membrane concentrate management

The management of membrane concentrate at the two manufacturing sites will differ slightly from each other since they have contrasting wastewater qualities. Other factors such as existing wastewater treatment facilities and wastewater tariffs can also influence the final decision on concentrate management.

3.5.1. Company A

The use of ceramic UF membranes for the pretreatment of the oily wastewater stream will generate reject water containing highly concentrated oil & grease as well as cathodic electrodeposition (CED) paint particles. This concentrate can be fed into the existing oily wastewater treatment system to eliminate the suspended particles present. The existing wastewater treatment system consists of a series of treatment processes such as coagulation, pH adjustment, flocculation, and dissolved air flotation. Subsequently, the treated UF concentrate can be mixed with the RO concentrate and treated further. The concentrate management method mentioned above is also applicable during reclamation of post-electrodeposition rinse wastewater.

The use of polymeric UF membranes to pretreat the metals wastewater stream will generate reject water containing highly concentrated suspended particles. Such reject water can be mixed with the reject water generated by the NF membrane which contains high levels of metals. The mixed UF and NF concentrate can be fed into the existing metals wastewater treatment system to

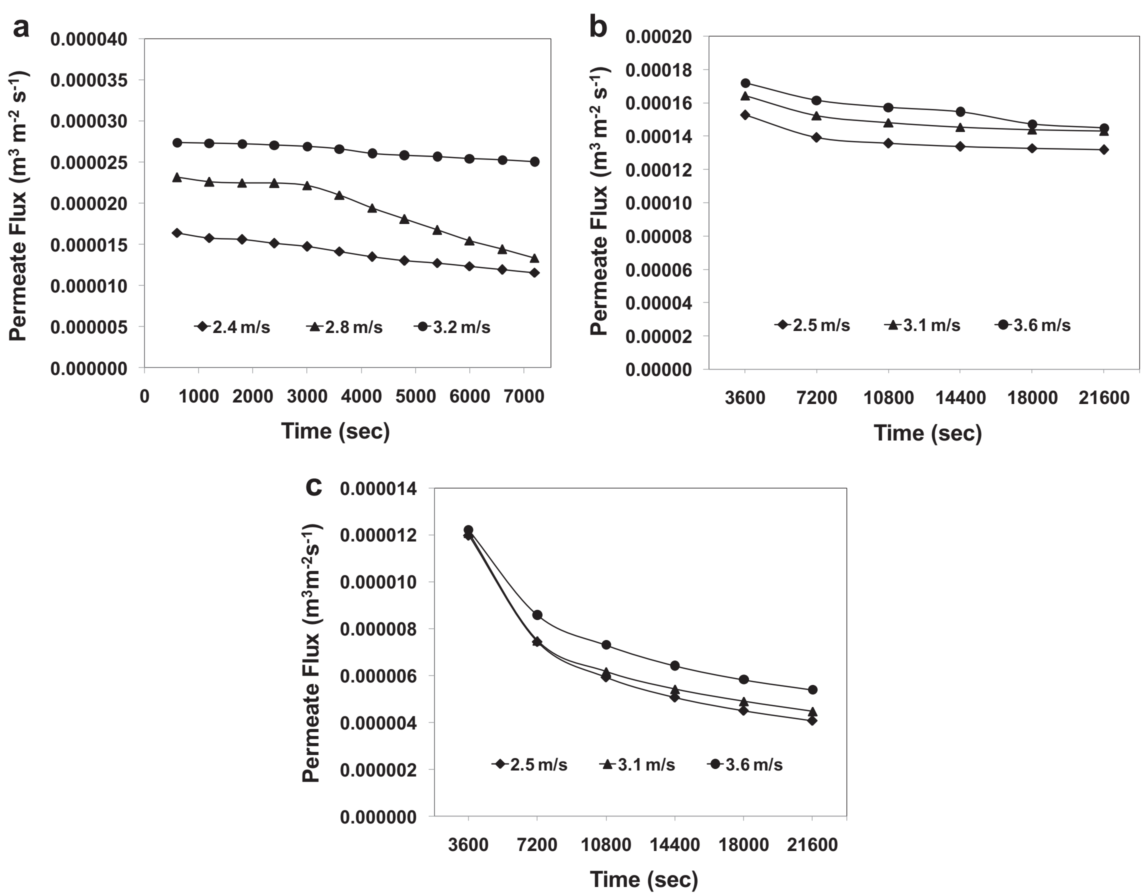

Fig. 13. Permeate flux rates of (a) 50 nm ceramic UF membrane applied to Company A's oily stream; (b) 5 nm ceramic UF membrane applied to Company B's Tradewaste discharge and; (c) JW membrane (PVDF-UF) applied to Company A's metals stream. Transmembrane pressure (TMP) used for all trials is 100 kPa. Permeate fluxes were normalized to a standard temperature of 20 °C.

Table 9
DL (NF) membrane performance on conductivity and specific metals rejection rates at different TMPs. Feed water into the NF membrane is Company A's metals wastewater stream. Average pH for the wastewater stream and product water is 3.7 and 3.9 respectively. Fw – feed water; Fl – filtrate; C_R – contaminant reduction/rejection rate.

TMP (kPa)	DL (NF) membrane											
	Cond. (μS/cm)			Mn (mg/L)			Ni (mg/L)			Zn (mg/L)		
	Fw	Fl	C_R (%)	Fw	Fl	C_R (%)	Fw	Fl	C_R (%)	Fw	Fl	C_R (%)
690	1605	546	65.9	23	0.03	99.9	40	0.03	99.9	99	0.12	99.9
1034	1542	522	66.1	24	0.06	99.8	42	0.08	99.8	100	0.28	99.7
1380	1640	511	68.8	24	0.05	99.8	41	0.04	99.9	100	0.19	99.8

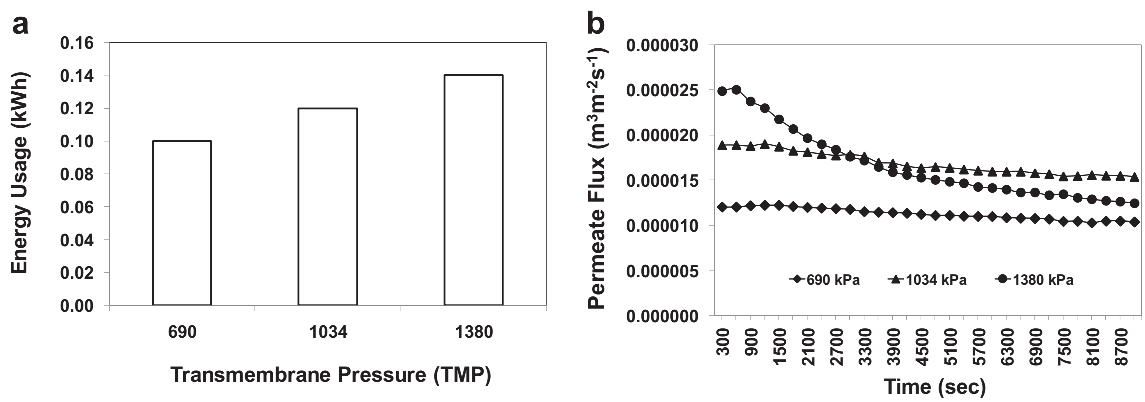

Fig. 14. NF membrane's (a) energy usage measured at different TMPs and; (b) permeate fluxes measured at different TMPs. Feed flow rate was maintained at 3.3E–5 m^3/s. Power rating of feed pump used is 0.37 kW. Permeate fluxes were normalized to a standard temperature of 25 °C.

eliminate suspended particles and specific metals such as Ni, Zn and Mn. The existing metals wastewater treatment system is composed of processes such as pH adjustment, flocculation and dissolved air flotation. The treated concentrates can be mixed together and treated further.

There are many commercially available technologies for treatment of membrane concentrate.

Some of the more promising technologies appropriate for company A's membrane concentrate include Wind Aided Intensified eVaporation (WAIV) and membrane distillation. WAIV technology is an enhancement of natural evaporation technology. Compared to natural evaporation, WAIV requires smaller land area and utilizes the drying power of the wind (Pérez-González et al., 2012). This technology increases evaporation rates by 50–90% (Pérez-González et al., 2012). On the other hand, membrane distillation is a promising technology, albeit not yet fully commercialized. It is quite different from other membrane technologies because it uses the difference in vapour pressure rather than total pressure to extract pure water from a membrane concentrate stream. Its major energy requirement is low-grade thermal energy which is readily available on industrial sites in the form of cooling tower feed, excess steam, generator exhaust, etc (Meindersma et al., 2005). The different types of membrane distillation include Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Sweep Gas Membrane Distillation (SGMD) and Vacuum Membrane Distillation (VMD). The typical operating temperature for membrane distillation ranges from 60 to 80 °C (Pérez-González et al., 2012).

The choice of concentrate treatment will depend on the company's goal. If Company A aims for zero liquid discharge, WAIV technology will be more suitable for membrane concentrate treatment. Alternatively, membrane distillation will be more suitable if Company A aims to recover pure water from the membrane concentrate.

The sludge generated from the treatment of the membrane concentrate can be sent off-site through a waste collection and treatment company. Such practice of sending sludge off-site for disposal and treatment already exists at company A.

3.5.2. Company B

Similar to Company A, the concentrate from the UF and RO membranes can be mixed together and subsequently treated using either WAIV or membrane distillation technology. The sludge generated from the treatment of the membrane concentrate can also be sent off-site through a waste collection and treatment company. After appropriate treatment (i.e. dewatering), the sludge can be dumped directly to landfill.

Table 10
RO membrane performance on the rejection of specific wastewater parameters such as conductivity, COD and TDS. Fw – feed water, Pw – permeate water; C_R – contaminant reduction/rejection.

Stream	TMP (kPa)	pH		Conductivity (μS/cm)			COD (mg/L)			TDS (mg/L)		
		Fw	Pw	Fw	Pw	C_R (%)	Fw	Pw	C_R (%)	Fw	Pw	C_R (%)
Oily	690	8.8	8.0	994	45	95.5	230	8.0	96.5	–	–	
		8.8	7.2	929	9	99.0	250	7.5	97.0	–	–	
Tradewaste	690	8.1	7.1	–	–		2300	69	97.0	2369	199	91.6
		8.4	7.2	–	–		3600	144	96.0	2650	229	91.4

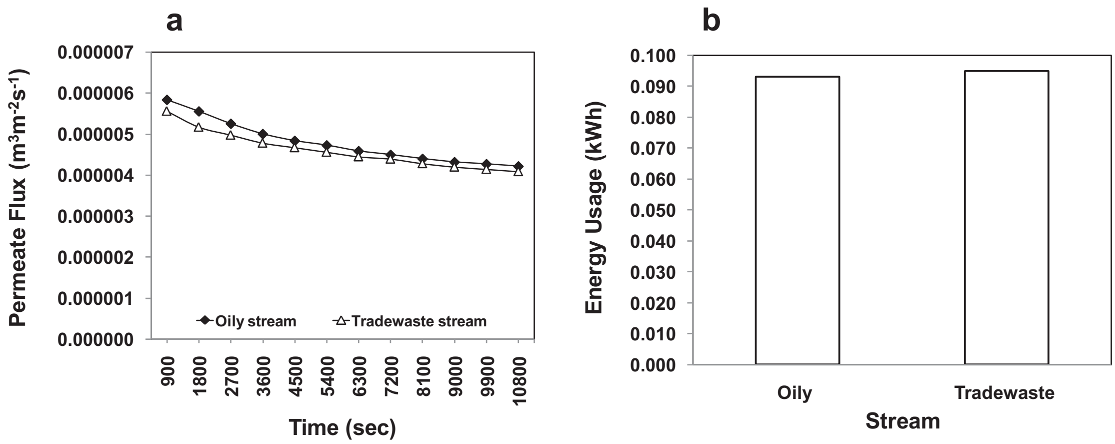

Fig. 15. RO membrane's (a) permeate fluxes measured at different wastewater streams and; (b) Energy usage measured at different wastewater streams. Feed flow rate and transmembrane pressure (TMP) were maintained at 3.3E−5 m^3s^{-1} and 690 kPa respectively. Power rating of feed pump used is 0.37 kW. Permeate fluxes were normalized to a standard temperature of 25 °C.

3.6. Estimated costs of the proposed membrane systems

The estimated costs of the proposed membrane systems for specific wastewater streams are shown in Tables 11–14. The formulas used in the cost calculations are given in Eqs. (4)–(11). The wastewater recycling rate was calculated using Eq. (4):

$$\%R_{WW} = W_R/WW_T \times 100\% \quad (4)$$

where % R_{WW} is the wastewater recycling rate; W_R is the volume of treated water for reuse per day, m^3; and WW_T is the total volume of wastewater generated per day, m^3.

The initial cost of equipment installation was calculated using Eq. (5):

$$C_I = C_E + C_M \quad (5)$$

where C_I is the total initial cost of equipment installation, $AUD; C_E is the equipment cost, $AUD; and C_M is the miscellaneous cost, $AUD. Miscellaneous cost includes civil works, connection set-up and freight. This cost was estimated using Eq. (6):

$$C_M = 0.05C_E \quad (6)$$

The total savings from wastewater recycling was calculated using Eq. (7):

$$S_T = FW_S + WW_S \quad (7)$$

where S_T is the total savings per year, $AUD; FW_S is the freshwater savings per year, $AUD; and WW_S is the actual wastewater savings per year, $AUD. Freshwater and actual wastewater savings per year were calculated using Eqs. (8) and (9) respectively:

$$FW_S = W_R \times C_W \times N \quad (8)$$

where C_W is the cost of freshwater per m^3, $AUD; and N is the number of days the manufacturing facility operates ($N \sim 240$ days).

$$WW_S = WW_{SI} - 0.2(WW_{SI}) \quad (9)$$

where WW_{SI} is the initial wastewater savings per year, $AUD. The initial wastewater savings per year was calculated using Eq. (10):

$$WW_{SI} = W_R \times C_{WW} \times N \quad (10)$$

where C_{WW} is the cost of wastewater per m^3, and N is the number of days the manufacturing facility operates ($N \sim 240$ days). The term $0.2 \times WW_{SI}$ in Eq. (9) is a cost provision that accounts for any increase in water quality parameters such as TDS, COD and BOD.

Finally, the payback period was calculated using Eq. (11):

$$P_P = C_I/S_T \quad (11)$$

As expected, the payback period for the proposed membrane systems generally shortens as the wastewater recycling rate is increased. Although this is the case, majority of the payback periods for the installation of specific membrane systems were above 4 years. The costs reveal that it is basically cheaper to discharge as Tradewaste the highly contaminated wastewater streams rather than installing wastewater treatment equipment such as membrane systems. This is because the current water tariffs in Australia are low – making on site treatment of wastewater undesirable.

For a single treatment system (i.e. UF system, Table 11), the wastewater recycling rate has a straightforward calculation. For example a 30% wastewater recycling rate would mean a volume of 76 m^3/day (30% of 253 m^3/day). But for a dual treatment system (i.e.

Table 11
Estimated cost of UF membrane system for reclamation of post-electrodeposition rinse wastewater ($WW_T = 253$ m^3/day).

% R_{WW}	C_I, $AUD ($C_E + C_M$)	S_T, $AUD/yr ($FW_S + WW_S$)	P_P, yrs – months
10.0%	105,000.00	680.63	154–4
30.0%	210,000.00	32,870.91	6–5
50.0%	315,000.00	65,061.18	4–10
70.0%	420,000.00	89,274.05	4–9
90.0%	525,000.00	114,178.21	4–8

Table 12
Estimated cost of ceramic UF and polymeric RO membrane systems for reclamation of oily wastewater stream ($WW_T = 578$ m^3/day; RO recovery = 75%).

% R_{WW}	C_I, $AUD ($C_E + C_M$)	S_T, $AUD/yr ($FW_S + WW_S$)	P_P, yrs – months
7.5%	257,250.00	4457.52	57–9
22.5%	467,250.00	44,263.53	10–8
37.5%	813,750.00	76,255.81	10–8
52.5%	1,128,750.00	115,759.85	9–10
67.5%	1,338,750.00	170,829.38	7–10

Table 13
Estimated cost of polymeric UF and NF membrane systems for reclamation of metals wastewater stream ($WW_T = 144\ m^3$/day; NF recovery = 75%).

% R_{WW}	C_I, $AUD ($C_E + C_M$)	S_T, $AUD/yr ($FW_S + WW_S$)	P_P, yrs − months
67.5%	94,500.00	47,392.41	2–0

Table 14
Estimated cost of ceramic UF and polymeric RO membrane systems for reclamation of beverage production wastewater ($WWT = 942\ m^3$/day; RO recovery = 75%).

% R_{WW}	C_I, $AUD ($C_E + C_M$)	S_T, $AUD/yr ($FW_S + WW_S$)	P_P, yrs − months
7.5%	362,250.00	20,215.69	17–11
22.5%	813,750.00	68,762.78	11–10
37.5%	1,233,750.00	140,085.14	8–10
52.5%	1,774,500.00	205,152.05	8–8
67.5%	2,194,500.00	264,330.89	8–4

UF and RO/NF systems, Tables 12–14), the wastewater recycling rate would mean a combination of the rates for both UF and RO/NF systems. For example, Table 12 shows a wastewater recycling rate of 67.5%. This percentage is equivalent to a volume of approximately 390 m^3/day (67.5% of 578 m^3/day). In order to obtain this volume, around 90% (520 m^3/day) of the total wastewater generated is reclaimed by the UF system. The filtrate obtained from the UF system is subsequently passed through an RO system at a recovery rate of 75%. The volume of the pure water after the RO system is 390 m^3/day.

The equipment cost estimates used in this section were obtained directly from the membrane manufacturers. Since costs were necessarily estimates only, there is a possibility that they may either increase or decrease depending on the final equipment design.

4. Conclusions

The in-series integrated water management strategy deployed here has been effective in systematically identifying possible water conservation opportunities at two large Australian manufacturing companies. Firstly, the water audit completely characterized all water streams found at both companies' production sites leading to the development of the water flow diagram and also identified some operational issues that could impinge on water management. The water flow diagram as well as the water test results obtained from the audit served as the basis for the succeeding strategies. Secondly, the process integration strategy which utilized commercially available water pinch software has successfully identified possible water reuse opportunities. These reuse opportunities were further evaluated and some were implemented on site with significant savings. Finally, the water recycling strategy showed the suitability of different membranes for treating specific wastewater streams. Results showed that the membranes tested have generally good contaminant rejection rates, slow flux decline rates and low energy usage.

The synergy of the different water management strategies deployed in this study can bring about substantial reduction of Citywater consumption and wastewater discharge. For example, it was shown at Company A that 33 tonnes/day of Citywater consumption was saved by directly reusing wastewater generated from other processes. Likewise, it was also shown at Company A that a further 80.8 tonnes/day of freshwater consumption can be saved through treatment of the post-electrodeposition rinse wastewater using an ultrafiltration process. The combined value of the Citywater savings for Company A will eventually translate to a wastewater reduction of approximately 16.1%. Meanwhile, for Company B, approximately 83.2 tonnes/day of Citywater can be saved just by reclaiming wastewater generated from different identified processes. The reclaimed wastewater will be treated by the conventional treatment system currently in operation at the production site and reused back into different water-using processes. This will translate into a wastewater reduction of approximately 8.6% for Company B.

The above water savings identified for both companies is, in fact, just the tip of the iceberg. The bulk of water savings will most likely come from wastewater treatment of the highly contaminated streams, Fig. 10, using appropriate low-pressure membranes. In this regard, the laboratory-scale membrane test rig has provided valuable information into the applicability of different low-pressure membranes for the reclamation of specific wastewater streams generated at both companies. By using the test rig, different operating parameters essential to the successful operation of such membranes used can be identified. Likewise, the use of test rig made it possible to effectively evaluate different low-pressure membrane candidates at much lower costs as compared to doing pilot-scale evaluations.

Although the results obtained so far are very promising, other issues such as applicability, membrane concentrate management and cost of commercial membrane equipment should also be researched further to completely assess the viability of their implementation. Results obtained from the process integration strategy are based on steady state assumptions and therefore implementation should always be checked against actual process operating conditions. It should be noted that the management of concentrate disposal is a long-standing problem for users of membrane technologies (Arnal et al., 2005; Sperlich et al., 2010). Therefore the proper disposal of membrane concentrate should be a primary concern for both companies since they have to satisfy the Tradewaste discharge limits imposed on them by the local water retailer. Likewise, the commercial cost of the membrane equipment should also be reliably known since the installation of such equipment will greatly depend on monetary values.

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