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Identifying water recycling strategy using multivariate statistical analysis for high-tech industries in Taiwan

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ABSTRACT

Multivariate statistical techniques of cluster analysis (CA) and discriminant analysis (DA) were applied in this study for the evaluation of water resource management strategies in high-tech industries, on the basis of the existing water use related data of 70 participating plants in Taiwan since 2011. The existing water use data were collected and transformed into detailed water balance charts, and the water use performance at individual plants was evaluated by three indices, namely the "processing water recovery rate", the "plant water recovery rate", and the "plant discharge rate". Results from discriminant analysis showed that increase in the ratios of effluent recycled to pure water system (EPWR) and recycled to secondary water system (ESWR) had positive effects on achieving higher water use performance. On the other hand, process water consumption and ESWR were influential factors in discriminating samples with lower water use performance. The results also confirmed the finding from synergistic effect that improvement on both EPWR and ESWR contributed to the highest water use performance. Opportunities for water recycling in high-tech industries appears to be technically feasible, future efforts could usefully be undertaken to implement further investment on water-use efficiency and novel treatment techniques, and investigation on various reuse purposes.

1. Introduction

Development of manufacturing-based economy comes with a price of increasing resource demands, as well as increasing wastes and effluents produced as byproducts of manufacturing. As extreme climate events may affect the circulation rate of available fresh water resources (Oki and Kanae, 2006), industries face many challenges, including limited water supplies and water use restriction, in addition to the increase in demands of waste minimization and pollution control (Gumbo et al., 2003). As a result, industry needs to be ready to take greater responsibility of resource-use efficiency and lean manufacturing, in particular to water resource management. An integrated water resource management with aspects of water reclamation, water reuse and water use efficiency is expected to contribute a long-term sustainability of water supply at community or global levels (Lee et al., 2011; Miller, 2006).

The high-tech industries, which generally refer to those produce microelectronics, communication and display devices, green-energy related appliances (e.g. solar panel) and biotechnology products, typically involve rinsing and cleaning procedures in the production lines that use extensive amount of ultra-pure water to avoid contamination-caused deficits in their products. Aside from water usage in production lines, water use in their secondary system (i.e. cooling tower and air scrubber) for environmental control is also high, as the environment in cleanrooms is required to be maintained at high standards (i.e. moderate temperature and low airborne molecule contamination). The water being used in the secondary system may not need to meet the ultra-pure water criteria, however, low concentrations in TOC as well as conductivity are expected to avoid fouling and corrosion problems under normal operations.

Increasingly stringent laws and environmental awareness affect the quantity and quality of the effluent discharge, which in return have motivated minimization of water use at source. As new plants are built, they are more likely than ever before to incorporate internal water recycling techniques as a means of avoiding the high cost of environmental compliance and retrofitting later on. Internal water reuse is especially preferable as the water-transporting

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associated energy consumption and environmental impacts (e.g. carbon emission) can be consequently avoided. Industries with implementation of sustainable practices such as water conservation or waste minimization also could put themselves in a better marketing position and a positive corporate image (Gumbo et al., 2003). The concept of resource recovery, which was expanded beyond resource efficiency, is advocated to minimize the ecological footprint of water sectors (Burn et al., 2012; Marlow et al., 2013). Water recovery, in particular, was demonstrated to have reduced environmental impacts comparing to the impacts from direct water consumption, especially when the reclaimed water was used for potable (Tong et al., 2013), non-potable purpose (Lens et al., 2002; Meneses et al., 2010) or replacement of desalinated water (Pasqualino et al., 2011).

One approach for water resource management in water-intensive industries is water network design, which includes design in both production and secondary use levels. Design of water network, by means of graphical methodologies (Alwi et al., 2008; Manan et al., 2006), mathematical programming (Feng et al., 2007) and synthesis of mass exchange networks (Shafiei et al., 2004), has been applied to allocate streams between operational units within the water system, due to the increased interests for sustainable development in industries (Boix et al., 2012). The purpose of water network design is to maximize water generation and reuse water into the industrial processes (El-Halwagi et al., 2003). Application of various water management strategies and practices are encouraged to be considered in the design of water network to embrace possible factors that may affect water supply–demand relationship within the water system. To be effective, water resource management should look into not only theoretical optimization values, but also investigate practical, behavior and strategically issues for holistic approaches (Seneviratne, 2007). Therefore, research efforts are needed to better understand the tools and strategies for implementation of successful water management projects.

Multivariate statistical techniques, such as cluster analysis (CA), factor analysis (FA) and discriminant analysis (DA), have had numerous applications in the aspect of water resource management that are generally used to interpret complex data matrices for a better understanding within the water systems. Cluster analysis (CA) is primary used to assemble objects with similarity based their characteristics. Discriminant analysis (DA), among all the multivariate statistical tools, is a classification technique that can be used to predict the group membership of a newly sampled observation with prior knowledge of objects' membership to a particular group or cluster. These analyses allow the identification of possible factors or sources that influence water related variations and offer a viable tool for water resource management (Liu et al., 2003; Shrestha and Kazama, 2007; Singh et al., 2004). Multivariate analysis has been utilized to characterize and evaluate water quality variations (Shrestha and Kazama, 2007; Singh et al., 2004; Vialle et al., 2011; Yidana and Yidana, 2010) as well as socio-economic factors in relation to environmental behaviors (Lee and Tansel, 2013; Robinson et al., 2005). Recent studies also employed multivariate analysis to relate sample characteristics (e.g. similarities or patterns between the sampling points) to environmental strategy development and performance evaluation (Aragón-Correa et al., 2008; do Couto et al., 2013; Molina-Azorín et al., 2009; Willis et al., 2011). Yet, discussions on the water management strategies for high tech industries were seldom reported. Giurco et al. (2011) presented a study regarding the development of a regional industrial water reuse networking with cost-effective and technically feasible water treatment and reuse options. However, the results still suffered from several disadvantages such as high investment costs comparing to direct on-site water use efficiency, complicated processing stages involving long distance water transportation, and high uncertainty in water quality management for directly reuse as a water source. Thus, further research efforts on the development of internal water recycling and reuse strategies within industrials' system boundaries are therefore needed.

This study first applies water auditing technique in reviewing water balance within the water system in high-tech industries, and then aims to provide a protocol for internal water recovery and reuse strategy development in the industries using results from multivariate statistical analyses, based on their water-use performances with current practices and possible technical improvements. A data metric of 70 participating plants is subjected to the analyses to extract information regarding similarities and dissimilarities between industries as well as identification of water-use performance responsible for successful water resource management. Synergistic interactions between the water-use-related determinants are also studied to further identify efforts to be made to promote sustainable water use in the industry. The results from this study could be useful for water resource planners for sharing lessons and implementation of strategies.

2. Methodology

2.1. Data collection and processing

In total, 70 plants were selected from the participant pool who joined the water conservation consultation program at three major science parks (HsinChu Science Park, Central Taiwan Science Park, and Southern Taiwan Science Park, based on their geographical locations from north to south in Taiwan) since 2011. These government-organized science parks mainly operate in the high-tech industries of integrated circuits, computer and peripherals, optoelectronics, telecommunications, biotechnology and green-energy. Corporates setting up in the science park with similar industrial characteristics are highly beneficial from economic (e.g. effective resource supply chain) and environmental perspectives (e.g. environmental protection and sustainable development) (Wang and Chiu, 2014). The water conservation consultation program offers service of strategy development for corporates who wish to improve their water use efficiency.

To better understand of water flows within the water system boundary, a water auditing technique using water balance chart (as shown in Fig. 1) was implemented to all the participating plants in this study (Barrington et al., 2013). Water balance charts were distributed and collected for all the participating plants. The charts are survey-based flow diagrams for identification of process flow, water and wastewater streams and possible water recycling routes within a defined boundary. It is worth noting that data collection for constructing the water balance chart is a lengthy process, as the process engages massive data processing of water usage and discharge, and intensive communication with the personnel to ensure accuracy in the chart. The use of water flow-balance charts may suggest abnormal water usage which cannot be identified during normal operations, and then be used to identify water saving opportunity within processes (Van der Bruggen and Braeken, 2006). In general, the abnormal water usage usually involves excess water losses from its system (e.g. steam leak or overflows), system leakage and unnecessary water use (e.g. prolonged gardening period during rain seasons).

As shown in Fig. 1, the water balance chart can be divided into three major water usages within the system, including water consumption for domestic uses (WD), secondary uses (WS) and processing uses (WP), which add up to total tap water consumption (W). Water use at domestic level usually refers to water usage related to human activities such as food processing and cleaning (e.g. wash hands and flush toilets). Secondary water usages in a plant normally are employed for cooling tower and