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An Integrated Graphical Approach for Industrial Water Conservation Project Selection

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Sustainable water management is one of the key measures to achieve Sustainable Development Goals. Increasing water consumption prompts industrial plants to implement water-saving projects and improve the utilization efficiency of water resources. This paper develops an integrated graphical method for designing an implementation path of water conservation projects that considers both water-saving targets and investment costs with or without subsidies. First, the cost-benefit analysis of each project is carried out. The unit water savings cost diagram is used to rank the priority of the implementation of each project. Then, the project mix which meets the expected water saving goal is determined by pinch analysis. Finally, the water conservation potential and cost-benefit of the optimal project mix are shown by the marginal cost curve diagram. This work presents two scenarios (i.e., with and without government subsidies). A chlor-alkali/ polyvinyl chloride complex is used as an illustrative case study. The complex achieves annual water savings of 3,580.4 kt by implementing the selected water conservation projects under the budget and subsidy constraints.

1. Introduction

Water is regarded as a critical factor in achieving sustainable development (World Bank, 2016). It is a critical resource that many industries rely on for various uses such as cooling, steam generation, product formulation, and washing (Jia et al., 2019). Water scarcity has become a major constraint to socio-economic development and a threat to livelihood in many parts of the world (Liu et al., 2017). Worldwide global water consumption has grown from 100 to 300 km^3/y in the past 50 y. It is projected to increase further to 550 km^3/y by 2050 (Wada and Bierkens, 2014). The water consumption in the industry is a major contributor to water demand. It is necessary to consider the water conservation problem for the industry sector if it chooses a sustainable development road. However, the water conservation issues in the industry are complex which involve the economic, social, and technical factors. The construction of a sustainable water management requires an integrated approach. It considers not only the end-of-pipe treatment of effluents, but also water conservation, reuse, regeneration and recycling, as well as the cost (Tan and Foo, 2018). A systematic method for water saving projects is required in order to achieve the goal of water reduction under the constraints of a fixed budget. In China, water intensity for the industrial sector has dropped to 6.68 L per Chinese Yuan in 2018, achieving a reduction of 18.9 % compared with that in 2015 (NOWC, 2019). However, there is still a big gap for the average water intensity level in developed countries (Mao, 2019). This big gap has prompted industrial sectors to select and implement water conservation projects (WCPs) to improve water efficiency. Carrero-Parreño et al. (2018) proposed a holistic planning method for sustainable water management in the shale gas industry. Li and Majozi (2018) presented a dynamic method for water management in the batch plant. Francisco et al. (2018) used Water Sources Diagram method to determine the water saving target for chemical plants with multiple contaminants. Kamat et al. (2019) proposed a linear mathematical formulation for optimal synthesis of a heat-integrated water network in which the conservation of energy and water is considered simultaneously. Li and

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Majozi (2019) provided an insight-based method for the design of batch water network with flexible production scheduling.
In literature, many efforts have been made to evaluate the potential of water saving for the industry and the optimal design of the water network. They focused on the technical and economic assessment of water saving strategies. For the companies, the selection of water saving projects should consider the economic constraints and the benefit of these projects. Because of the fund constraints, there may be many water saving projects which can be implemented simultaneously. A systematic method is required to ensure the selected projects are efficient. This paper focuses on an integrated graphical approach to determine optimal WCP mix that considers water-saving targets and limited investment funds with/without subsidies from local government. The cost-benefit analysis of the water saving projects is performed first. Next, based on the results of cost-benefit analysis, the selection process of water saving projects is visualized graphically. It provides a systematic approach to identify the optimal project mix to meet the water saving goal and the fund constraints.

2. Methodology

The schematic diagram of the integrated graphical approach for WCP selection is shown in Figure1. First, the data that are used in the integrated approach are specified. The extraction of wrong data could result in the waste of budget and risks to the plant. Systematic WCP data include water prices, fixed investment, funds, water-saving targets, and subsidy. Next, Cost-Benefit Analysis (CBA), Pinch Analysis (PA), and Marginal Water Saving Cost Curve (MWSCC) are combined to determine the priority of water saving projects. The unit water-saving cost diagram derived from CBA is then used to rank the priority of implementation of each proposed project. The PA diagram is used to determine the optimal project mix which meets the expected water-saving goal. The MWSCC will be presented to water saving potential and implementation path. Two scenarios are considered for WCPs selection, i.e., (1) with and (2) without government subsidy.

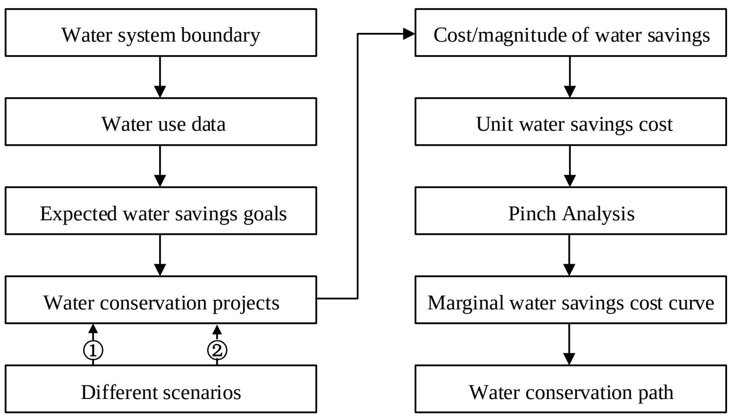

Figure 1: Framework for WCPs selection

2.1 Cost-Benefit Analysis

CBA is a well-known method used to make business decisions. It evaluates the value of a project by comparing its total costs and benefits (Boardman et al., 2017). CBA consists of estimating the total costs of a particular decision, and then comparing them to the estimated benefits of that decision. The main CBA steps are as follows:
Step 1: Specify the set of projects based on available funding and technologies.
Step 2: Decide whose benefits and costs count.
Step 3: Calculate the net present value of each project. Net present value (NPV) is equal to the difference between the present value of benefits (PV(B)) relative to the present value of costs (PV(C)), as shown in Eq.1.

$$NPV=PV(B)-PV(C) \quad (1)$$

Step 4: Calculate the marginal cost for water saving (MCsw). Divide annual NPV by annual water saving (AWS) to get the marginal cost, as shown in Eq.2.

$$MCsw=NPV/AWS \quad (2)$$

Step 5: Determine priorities for project implementation based on MCsw.

2.2 Pinch Analysis

Pinch Analysis is an insight-based methodology for Process Integration (PI) problems. It was originally developed to optimize heat recovery in process plants, but over four decades of development, applications have diversified to address different sustainability issues (Klemeš et al., 2018). In this work, PA for WCPs is extended from the selection of various CO_2 emissions reduction projects (Tan et al., 2016) and energy conservation projects (Roychaudhuri et al., 2017). For the detailed mathematical formulation, the reader can refer to Tan et al. (2016).
Step 1: All WCPs are arranged in ascending order of actual water savings intensity. Water savings intensity refers to the ratio between magnitude of water savings and financial investment for a given project.
Step 2: Magnitude of water savings is used for horizontal coordinate, financial investment as the vertical. A composite curve of WCPs is plotted according to the ascending order of actual water savings intensity.
Step 3: All financial resources are arranged in the ascending order of expected water savings intensity. Note that in most cases, the company set the expected water savings intensity of financial resources according to the expected water saving goal.
Step 4: According to the ascending order of water savings intensity, the composite curve of financial resources and WCPs are plotted in the same coordinate system. The fund composite curve is shifted along the project composite curve until all the fund composite curve is below the project composite curve.

2.3 Marginal Water Savings Cost Curve (MWSCC)

The quantified total water saving potential and marginal cost for all WCPs are used to construct the cost curve. This cost curve sorts the results from the most cost-effective WCP to the least cost-effective one from left to right. The height of the bar is the marginal cost of the WCP. A negative value means that both monetary and water savings result from a project, while a positive value means that water is saved at the expense of financial investment cost. The width of the bar is the total amount of water saved over the assessment period, while the area of the bar is the net cost of the WCP.

3. Case Study

The chlor-alkali/polyvinyl chloride (PVC) industry is a major basic chemical industry. China now accounts for about one-third of global PVC output and consumption. This sector is also a very water-intensive industry. Most of the PVC industrial plants are located in water scarce areas, leading to water stress both for these companies and the neighbouring communities (Wang et al., 2019). Based on these conditions, a chlor-alkali/ polyvinyl chloride complex is used in this work as an illustrative example. The system boundary of this case study is shown in Figure 2. The detailed description of the production chain can be found in Wang et al. (2019). This firm plans to invest up to $ 1.05 M to improve the water use efficiency and to achieve water saving goal of 1. 575 Mt/y. The expected water savings intensity is 1.5 t/$. Assuming that the water supply system of the case study runs steadily, eleven WCPs (i.e., P1 to P11) are specified. Their data are shown in Table 1 (Dai et al., 2015).

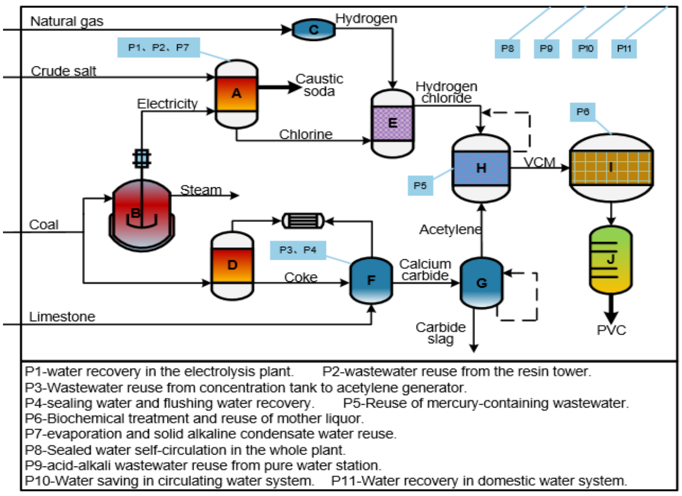

Figure 2: The system boundary of the case study

Table 1: Data for WCPs

Project	Water-saving (kt/y)	Investment (k$)		Water savings benefit (k$)		Payback period (y)	
		Without subsidy	With subsidy	Without subsidy	With subsidy	Without subsidy	With subsidy
P1	100.4	5.8	4.9	37.8		0.153	0.13
P2	100	217	184.5	1,034.8		0.21	0.178
P3	144	14.5	12.3	54.4		0.267	0.226
P4	96	7.3	6.2	36		0.203	0.172
P5	26.4	869.6	434.8	-50.3	-22.5	-	-
P6	722	950	807.5	142		6.69	5.493
P7	640	144.9	123.2	527		0.275	0.234
P8	224	156.5	133	239.2		0.654	0.556
P9	216	36.2	30.8	81		0.447	0.38
P10	1800	785	667.3	676.5		1.16	0.986
P11	360	30	25.5	136.7		0.219	0.187

3.1 Scenario 1

This scenario assumes that the WCPs are to be considered without subsidy. The cost per unit of water savings for each project is investigated first. The unit water savings cost diagram is plotted as shown in Figure 3. It can be seen that the water saving costs of units P2, P7, P8, P1, P4, P11, P3 and P9 are negative, which means that the first year of implementation of each of these projects is already profitable, and the funds invested are recovered rapidly. The unit water savings cost of P10, P6 and P5 are positive, which means that the complex cannot recover the investments for any of these projects within 1 y. Due to the large fixed investment of P10 and P6, the payback period is more than 1 y. The mercury-containing wastewater recycling project of vinyl chloride workshop (P5) is costly and has low effectiveness. From the perspective of the cost-benefit perspective, the priority of project implementation is P2, P7, P8, P1, P4, P11, P3, P9, P10, P6, and P5.

Based on the project water savings investment and magnitude of water savings, we obtain the water savings intensity of each project. A pinch diagram for WSPs is plotted as shown in Figure 3b. It can be seen that the water saving intensity of projects P10, P7, P9, P3, P11, P4, and P1 is higher than the expected intensity. The total investment of water saving in the complex is 1,023.7 k$. Based on the selected WCP mix, a MWSCC can be drawn as shown in Figure 4. The selected WCP portfolio can save water 3,356.4 kt/y.

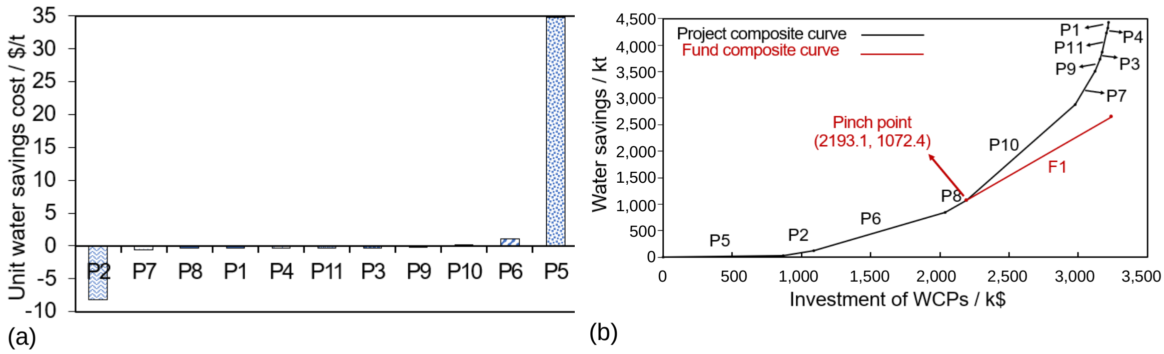

Figure 3: (a) Unit cost diagram without subsidy (b) Pinch diagram for WCPs without subsidy

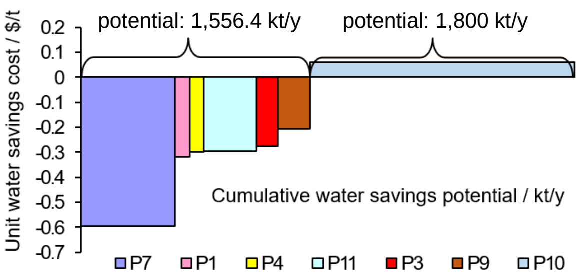

Figure 4: MWSCC for WCP mix without subsidy

3.2 Scenario 2

This scenario examines the effect of government subsidy to improve water use efficiency and wastewater reduction. Industrial companies can apply for water saving financial subsidies every year, but every project can only be subsidized once. The policy is as follows. The first category is designed for subsidy of cooling water, washing water, tail water, general wastewater, and boiler condensate recycling facilities, at 15 % of the actual investment of the project. The maximum subsidy for a single project cannot exceed 150 k$. The second category is designed for special wastewater treatment projects (e.g., mercury-containing wastewater). This subsidy covers 50% of the actual investment, and the maximum subsidy for a single project cannot exceed 725 k$. Based on these policies, projects P1, P2, P3, P4, P7, P8, P9 fall into the first category, and P5 falls into the second category.
We revisit the costs and benefits of the subsidized WCPs as shown in Figure 5. The priority of project implementation changes to P2, P7, P8, P1, P4, P11, P3, P9, P10, P6, and P5. The unit cost of water savings in all projects is lower than before the subsidy. As can be seen from Figure 5b, the complex is expected to achieve an annual water savings of 1,575 kt, which requires a total budget of 1,050 k$ to meet the investment requirements for P8, P10, P7, P9, P3, P11, P4, and P1.

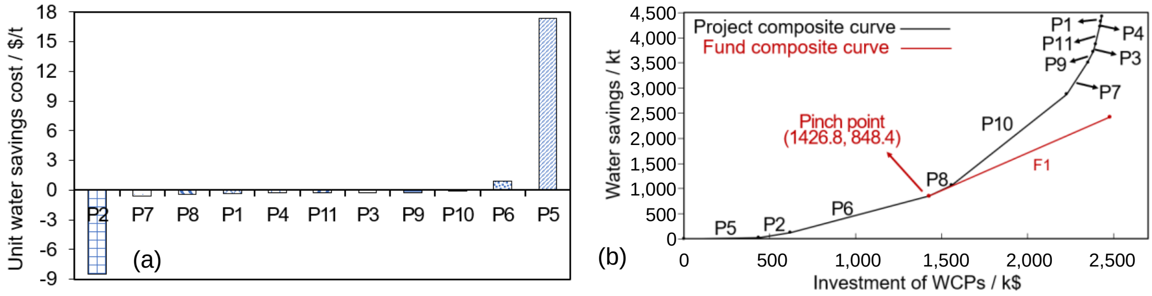

Figure 5: (a) Unit water savings cost diagram with subsidy (b) Pinch diagram for WSPs with subsidy

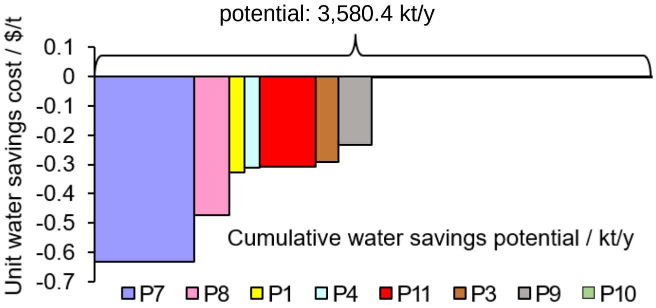

Figure 6: MWSCC for WSP mix with subsidy

The MWSCC is replotted as shown in Figure 6. The complex achieves annual water savings of 3,580.4 kt by implementing the selected WCPs. Projects P1, P3, P4, P7, P8, P11, P9, and P10 can recover the investment in the first year. Note that P10 can only recover the investment in the first year if there is a subsidy. It can be seen that government support via subsidy improves the water saving capacity and the efficiency of water use efficiency for the complex.

4. Conclusions

In this paper, a graphical approach is presented to select water conservation projects subject to financial constraints. A cost-benefit analysis of water saving projects is performed to determine the water saving intensity of each project. Pinch Analysis is extended to select the project to be implemented. Finally, a case study with two scenarios are used to apply the proposed method. The integrated framework can be used as a decision-making tool that can be used to select and rank WCPs. The method can account for government subsidies for WCPs that can effectively promote water-saving project implementation. However, the limitation of this work is that the water saving potential is not evaluated based on rigorous approach. In future work, water integration method and the time value of money should be incorporated into the proposed method. Also, chemicals recovery in WCP needs to be considered. Co-benefit analysis should drive industrial managers to examine every possible profit to save both water and chemicals. Sensitivity analysis should also be performed to examine how conclusions might change subject to techno-economic uncertainties.

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