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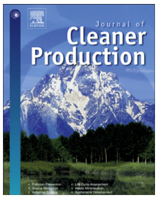

# A holistic approach for design of Cost-Optimal Water Networks

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## ABSTRACT

This work presents a holistic approach for design of Cost-Optimal Water Networks (CWN) that considers the economics while exploring all water minimisation options in line with the water management hierarchy (WMH). Two stages are involved in analysing the model i.e., the freshwater saving mode (FWS-mode) and the economic mode (E-mode). The first stage applied the mixed integer linear program (MILP) formulation that yielded some initial values for the second stage. In the second stage, the model was formulated as a mixed integer nonlinear program (MINLP) that was used to optimise an existing water systems design. The novelty of the model lies in the simultaneous considerations of all levels of water management hierarchy (i.e. elimination, reduction, reuse, outsourcing and regeneration) and cost constraints in selecting the best water minimisation schemes that resulted in the maximum net annual savings at a desired payback period. The model is applicable for systems involving multiple contaminants, and is capable of predicting which water demand should be eliminated or reduced; how much external source is needed; which wastewater source should be reused/recycled, regenerated or discharged; and finally specify the minimum water network configuration for maximising the net annual savings at a desired payback period. The model has been successfully applied on case studies involving a building (Sultan Ismail Mosque, UTM) and an industrial process plant (a chlor-alkali plant).

## 1. Introduction

Rapid economic development and population growth have contributed to rising water consumption globally. Wang et al. (2015) reported that China, which is the world's largest water consumer, consumes about 24.03% from total water demand in China, resulting in an estimated 23.75 billion t of wastewater discharge in 2010.

Varbanov (2014) relates the increasing demand of water supply and energy causes the scarcity of both resources. Widespread awareness and concern over the security and sustainability of water supply have driven industries to explore various cost-effective strategies for efficient water usage beyond the end-of-pipe treatment of wastewater. Freshwater demand in industry and the effluent generated can be reduced via the adoption of water minimisation techniques, leading to reduced cost associated to water procurement and effluent treatment.

Extensive research effort has been focused on minimising freshwater and the cost associated in designing optimal water networks. Insight-based graphical methodology as well as mathematical modeling have been utilised in the design of optimal water networks to achieve the minimum total cost. Foo (2009) reviewed the conceptual approaches for water network synthesis, with the main aim to minimise freshwater cost while meeting the environmental discharge limit. The network synthesis between water-using and water-regeneration operation are optimised using certain objectives and satisfy constraints especially on water flow rates and impurity load balances. The challenges highlighted in the study include the lack of water network synthesis development for retrofit cases as well as the issue of establishing water network capital costs target for fixed flowrate problem (water flowrate minimisation). Another water system design which incorporate water-using and treatment system also reviewed by Jezowski

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(2010). Methodologies for water system targeting and design based on mathematical programming as well as on the conceptual approach for network synthesis have been performed with the typical goal of minimising the total annual cost. Klemes (2012) employed the fundamental understanding of water and wastewater minimisation by reviewing both typical Pinch Analysis (conceptual approach) and mathematical programming techniques. The study indicates that the water network economic criteria such as the freshwater cost, piping and pumping should be optimised together to develop a realistic water network. A better water network design for more complex problem can be solved using mathematical programming techniques.

A recent work on water minimisation is the development of optimal water network by Ying and Jintao (2016). The authors developed the regeneration water network structure and provide a step by step guide in developing regeneration-reuse and regeneration-recycling as an insight for the next design of water-using network using mathematical modeling technique. The work provides the minimum freshwater flowrate as well as the minimum recycle water flowrate.

Several other researches on water network synthesis that are associated with total cost minimisation have been developed. An example is the model developed by Alva-Argaez et al. (1998) who used the total cost as an objective function for the optimal design of industrial water system. Alva-Argaez (1999) then formulated the water system design problem as a Mixed Integer Non-Linear Programming (MINLP) model which was then decomposed into Mixed Integer Linear Programming (MILP) and Non-Linear Programming (NLP) for solving the mathematical formulation. The authors targeted the minimum total annual investment as well as the minimum operating cost for the water-using network that considers water reuse. An optimum solution consolidating all the functional constraints was the main purpose of their model. However, their model was not applicable for retrofit scenarios as there was no details in their development of water network system even though the water reuse, regeneration-reuse and regeneration recycling were considered.

A complex trade-off which included capital and operating cost was considered in the work by Gunaratnam et al. (2005) in solving total water system problem. The work is able to simultaneously design water-using system and effluent treatment considering control and safety, geographical layout as well as minimum or maximum allowable flowrates.

In their work of optimisation of industrial water network, Faria et al. (2009) used mathematical modeling technique to focus on freshwater minimisation as their primary objective and further looked into the operating cost optimisation as their secondary objective. Using an NLP to describe the model, all possible forms of water and wastewater minimisation technique such as reuse with and without regeneration, as well as water recycling, were considered for the network. The initial analysis of this study successfully presented the minimum water consumption within the process although it does not result in the lowest operating cost for the network. The study requires augmenting procedures such as the network operability, risk analysis and layout analysis to improve the developed model and improve the water network cost by formulating more equations that are specific to regeneration.

Handani et al. (2010) has modelled the Minimum Water Network and considered all water minimisation options in WMH that resulted in reduction of freshwater usage using a mathematical programming technique. However, the work has not included economic analysis in the development of the model.

A mathematical modeling technique was used by Lim et al. (2007) to maximise water network system profitability using NLP model. They applied the incremental cost of piping, maintenance and repair, pipe decommissioning and freshwater consumption into a conventional water network to rearrange the network into a cost-effective water network system. Another work based on profitability for water network systems was developed by Faria and Bagajewicz (2009). They performed mathematical optimisation for grassroots and retrofit cases involving single and multiple contaminants and considered the regeneration process. The net present value and return of investment were maximised.

Even though cost constraints have been successfully considered in developing a profitable water network by other researchers, Poplewski et al. (2010) however, faced some issues in estimating the piping investment from a general linear formulation for the industrial practice. The developed basic model was found to eliminate one of the attractive networks which had minimised the cost or freshwater, due to some structural issues. Kim (2012) later included freshwater cost, treatment cost as well as piping cost in the development of their total water system design. The work highlighted an improved water network which included water reuse within the operation. A graphical method and mathematical optimisation techniques were used for the system-wide analysis in which the relevant economic trade-offs such as freshwater cost, treatment cost, wastewater discharge and piping cost were considered. Novak et al. (2014) discussed the influence of piping cost in their investment. Their work included the pipeline connections between water-using operations and treatment units. However, the solution obtained was not economically efficient when freshwater cost is minimised.

A water conservation network retrofit study was done by Sotelo-Pichardo et al. (2011), favouring schemes such as water reuse, recycle and regeneration using mathematical programming method. The problem was modelled using MINLP that considers minimisation of total annual cost as their objective function. The formulation includes freshwater cost, existing treatment unit expansion and treatment unit addition. The results revealed the option of upgrading the existing treatment units rather than installing new treatment units, leading to the minimum total annual cost. Based on the retrofitted network, the freshwater consumption was greatly reduced when water sources were reused and recycled within the network. The model can be modified to suit different objectives functions, the proper piping and pumping costs can be easily determined and other constraints such as safety and operability can be considered.

Ahmetović et al. (2014) in their work considered the total annual cost minimisation in their design of heat-integrated water-using and wastewater treatment network (HWTN). The network problem considered complex trade-offs involving the capital and operating costs as well as other practical constraints such as freshwater usage, hot and cold utilities consumption and wastewater treatment units. The network was then formulated as a non-convex mixed integer non-linear programming. The approach is capable of providing a simultaneous solution strategy such as the appropriate trade-offs between freshwater and utilities consumption as well as investment for heat exchangers and wastewater treatment units.

Bozkurt et al. (2015) in their preliminary design of municipal wastewater treatment plants, presented a MINLP model which described the optimisation based on mathematical programming to identify optimal process technologies for retrofit design of wastewater treatment plants. The model attempted to minimise the total annual cost which was defined as the summation of operational (OPEX) and capital cost expenses (CAPEX). Ouyang et al. (2015) developed a hierarchy framework to select the foremost technology for wastewater treatment system where the prime target was to obtain the maximum profits. It involved the consideration of capital cost, maintenance cost and other indices. A further attention on the contradictory result between the