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# Synthesis of industrial park water reuse networks considering treatment systems and merged connectivity options

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ABSTRACT

A number of optimization approaches for the synthesis and design of effective wastewater regeneration and reuse networks in industrial parks have been proposed to support decision making for careful management of water resources by the industrial sector. The approaches allow the identification of optimal wastewater treatment and reuse strategies. All such available methods for interplant water network synthesis assign a single pipeline for every viable water allocation identified, which results in inefficient and costly pipe networks. Instead, this work presents a water network design approach that accounts for a number of pipeline merging scenarios for wastewater reuse and regeneration networks considering central and decentral treatment options. Merging common pipe segments that carry similar water qualities allows for cost-improvements in network design, in addition to reducing the overall pipeline network complexity due to fewer required interconnecting pipes. The benefits of the proposed method are illustrated with a case study.



## 1. Introduction

Industrial water and wastewater management has become a research priority in many regions, due to the vast scale of water-intensive activities in many industrial operations, which in turn are continually increasing as a result of industrial expansion initiatives. Moreover, industrial sites that lie in proximity to coastal areas involve large volumes of unused wastewater being diverted back into the sea, which negatively impacts aquatic life (Englert et al., 2013). Industrial wastewater reuse certainly alleviates the depletion of available freshwater sources that are present around industrial areas. Hence, wastewater reuse also helps reduce the excessive wastewater quantities being discharged back into natural water bodies. Identifying appropriate wastewater treatment alternatives is considered of significant importance due to the stringent discharge limits being imposed on industrial wastewater, as well as the strict effluent standards that industries are expected to adhere to. Potential opportunities for industrial wastewater reuse (Ehrenfeld and Gertler, 1997) would absolutely vary from one industry to another, depending on the quantity and quality of wastewater produced.

The design of cost-effective wastewater regeneration and reuse networks has been the primary focus of many previous studies. Chew et al. (2008, 2009) developed a centralized hub topology that involves the collection, treatment and distribution of water amongst coexisting plant arrangements within an industrial zone. Rubio-Castro et al. (2010, 2011) devised a Mixed Integer Non-Linear (MINLP) optimization model for interplant water networks whilst incorporating environmental regulations for wastewater discharge. Additionally, a reformulation of the same problem has also been proposed, which handles bilinear terms involved. Several Multi-objective optimization strategies for water network design in Eco-Industrial Parks have also been studies by Biox et al. (2012). More recent research contributions in the field of water network design have also been proposed. For instance, a structured representation that is capable of capturing the spatial aspects of water network design (Alnouri et al., 2014a) has been introduced in which effective planning of wastewater reuse networks has been handled with a focus on the following aspects: (1) accounting for site locations and the spatial distribution of all plant entities that lie within geographic proximity within an industrial zone(2) the ability of incorporating layout information associated with processing facilities that entail water use or production, (3) capturing information related to the presence of common city infrastructure, such as the

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**Nomenclature**

*Indices*

| | |
|---|---|
| $a$ | First level node associated with pipeline branching |
| $b$ | Second level node associated with pipeline branching |
| $c$ | Third level node associated with pipeline branching |
| $n$ | Nth level node associated with pipeline branching |
| $i$ | Water Source |
| $j$ | Water Sink |
| $p$ | Plant/Process |
| $r$ | De-central treatment |
| $s$ | Central treatment |
| $t$ | Type of central treatment |

*Sets:*

| | |
|---|---|
| $N$ | Set of nth level nodes n (must be defined for every merged connection) |
| $P$ | Set of Plants/Processes in Industrial City |
| $R$ | Set of Decentralized Treatment Interceptors r |
| $SU_p$ | Set of Water Sources in Plant p |
| $SN_p$ | Set of Water Sinks in Plant p |
| $S$ | Set of Central Treatment Interceptors |
| $T$ | Set of Central Treatment Interceptor Types |
| $X$ | Set of first level nodes a (must be defined for every merged connection) |
| $Y$ | Set of second level nodes b (must be defined for every merged connection) |
| $Z$ | Set of third level nodes c (must be defined for every merged connection) |

*Parameters:*

| | |
|---|---|
| $a$ | Coefficient associated with piping cost calculations |
| $b$ | Power coefficient associated with piping cost calculations |
| $C_{rp}^{INV}$ | Decentralized Treatment r within Plant p Unit Cost ($) |
| $C_{st}^{INV}$ | Central Treatment Type t Unit Cost ($) |
| $C_{rp}^{REM}$ | Decentralized Treatment r within Plant p mass removed Cost ($/kg) |
| $C_{st}^{REM}$ | Central Treatment Type t mass removed Cost ($/kg) |
| $C^{WASTE}$ | Cost of Wastewater Discharge ($/kg) |
| $C_{l}^{FRESH}$ | Cost of Freshwater of type l ($/kg) |
| $\Delta DI$ | Pipe diameter difference (m) |
| $G_{jp}$ | Flowrate required in sink j, plant p (t/h) |
| $H_{y}$ | Operating hours per year (h/yr) |
| $K_{F}$ | Treatment Annualized Factor (yr$^{-1}$) |
| $L$ | Length of pipe segment (m) |
| $RR_{c,rp}$ | Removal Ratio of pollutant c in treatment interceptor r, plant p |
| $RR_{c,st}$ | Removal Ratio of pollutant c in central treatment interceptor s of type t |
| $W_{ip}$ | Flowrate available in source i, plant p (t/h) |
| $x_{c,ip}^{Source}$ | Pollutant c composition in source i, plant p (ppm) |
| $x_{c,l}^{FRESH}$ | Pollutant c composition in External Freshwater of type *l* (ppm) |
| $x_{c}^{Max}$ | Maximum permissible discharge concentration of pollutant c (ppm) |
| $x_{c,l}^{FRESH}$ | Pollutant c composition in External Freshwater of type *l* (ppm) |
| $z_{cj,p}^{min}$ | Minimum permissible pollutant c composition in sink j, plant p (ppm) |
| $z_{c,jp}^{max}$ | Maximum permissible pollutant c composition in sink j, plant p (ppm) |
| $\rho$ | Density in kg/m$^3$ |
| $\gamma$ | Annual cost factor (1/yr) |

*Variables:*

| | |
|---|---|
| $D_{rp}$ | Wastewater mass flowrate discharged by interceptor r, plant p (kg/h) |
| $D_{st}$ | Wastewater mass flowrate discharged by central interceptor s of type t (kg/h) |
| $D_{ip}$ | Wastewater mass flowrate discharged by source i, plant p (kg/h) |
| DI | Diameter of pipe segment (m) |
| DC | Calculated diameter of pipe segment (m) |
| FC | Total Freshwater Costs ($/y) |
| $F_{l,jp}$ | External freshwater mass flowrate of type l required in sink j, plant p (kg/h) |
| $M_{ip,jp'}$ | Mass flowrate from source i, plant p to sink j plant p'(kg/h) |
| PCM | Total Piping Costs associated with source-sink merged connectivity($) |
| PCDT | Total Piping Costs associated with source-to-decentralized treatment, and de-centralized treatment-to-sink merged connectivity ($) |
| PCCT | Total Piping Costs associated with source-to-centralized treatment, and centralized treatment-to-sink merged connectivity ($) |
| PCD | Total Piping Costs associated with decentralized treatment-to-waste, centralized treatment-to-waste, and source-to-waste merged connectivity ($) |
| PCF | Total Piping Costs associated with freshwater-to-sink merged connectivity ($) |
| $T_{ip,rp}$ | Mass flowrate from source i, plant p to interceptor r plant p (kg/h) |
| $T_{ip,st}$ | Mass flowrate from source i, plant p to interceptor s of type t (kg/h) |
| $T_{rp,jp}$ | Mass flowrate from interceptor r plant p to sink j, plant p (kg/h) |
| $T_{st,jp}$ | Mass flowrate from interceptor s of type to sink j, plant p (kg/h) |
| TDC | Total Central Treatment Costs ($/y) |
| TCC | Total De-central Treatment Costs ($/y) |
| WC | Total Wastewater Discharge Costs ($) |
| $x_{c,rp}^{in}$ | Inlet concentration of contaminant c into interceptor r, plant p (ppm) |
| $x_{c,rp}^{out}$ | Outlet concentration of contaminant c into interceptor r, plant p (ppm) |
| $x_{c,st}^{REM}$ | Total mass removed of contaminant c in interceptor r, plant p (ppm) |
| $x_{c,st}^{in}$ | Inlet concentration of contaminant c into central interceptor s of type t (ppm) |
| $x_{c,st}^{out}$ | Outlet concentration of contaminant c into central interceptor s of type t (ppm) |
| $x_{c,st}^{REM}$ | Total mass removed contaminant c in central interceptor s of type t (ppm) |
| $x_{c}^{Discharge}$ | Total discharge concentration of contaminant c |
| $y_{st}$ | Binary variable associated with interceptor s utilizing type t central treatment |
| $z_{c,jp}^{in}$ | Pollutant c Composition in sink j, plant p (ppm) |