Incremental design of water symbiosis networks with prior knowledge: The case of an industrial park in Kenya

Ramin, Elham; Bestuzheva, Ksenia; Gargalo, Carina L.; Ramin, Danial; Schneider, Carina; Ramin, Pedram; Flores-Alsina, Xavier; Andersen, Maj M.; Gernaey, Krist V.

Published in:
Science of the Total Environment

Link to article, DOI:
10.1016/j.scitotenv.2020.141706

Publication date:
2021

Document Version
Peer reviewed version

Citation (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
Incremental Design of Water Symbiosis Networks with Prior Knowledge: the Case of an Industrial Park in Kenya

Elham Ramin\textsuperscript{a*}, Ksenia Bestuzheva\textsuperscript{b}, Carina L. Gargalo\textsuperscript{a}, Danial Ramin\textsuperscript{c}, Carina Schneider\textsuperscript{d}, Pedram Ramin\textsuperscript{a}, Xavier Flores Alsina\textsuperscript{a}, Maj M. Andersen\textsuperscript{e}, Krist V. Gernaey\textsuperscript{a*}

\textsuperscript{a}Department of Chemical and Biochemical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark

\textsuperscript{b}Konrad-Zuse-Centre for Computer Science and Applied Mathematics Berlin (ZIB), Berlin, Germany

\textsuperscript{c}Institute of Intelligent Industrial Technologies and Systems for Advanced Manufacturing, CNR, Milan, Italy

\textsuperscript{d}Department of Environmental Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark

\textsuperscript{e}Department of Technology, Management and Economics, Technical University of Denmark, Kgs. Lyngby, Denmark

\textsuperscript{*}Corresponding authors: elhr@kt.dtu.dk; kvg@kt.dtu.dk
Abstract

Industrial parks have a high potential for recycling and reusing resources such as water across companies by creating symbiosis networks. In this study, we introduce a mathematical optimization framework for the design of water network integration in industrial parks formulated as a large-scale standard mixed integer non-linear programing (MINLP) problem. The novelty of our approach relies on i) developing a multi-level incremental optimization framework for water network synthesis, ii) including prior knowledge of demand growth and projected water scarcity to evaluate the significance of water saving solutions, iii) incorporating a comprehensive formulation of water network synthesis problem including multiple pollutant and different treatment units and iv) performing a multi-objective optimization of the network including freshwater savings and relative cost of network. The significance of the proposed optimization framework is illustrated by applying it to an existing industrial park in a water scarce region in Kenya. Firstly, we illustrated the benefits of including prior knowledge to prevent an over-design of network at early stages. In the case study, a more flexible and expandable water network with 36% lower unit cost at the early stage and 15% lower unit cost at later stages for the overall maximum fresh water savings of 25%. Secondly, multi-objective analysis suggests an optimum freshwater savings of 14% to reduce the unit cost of network by half. Moreover, the significance of symbiosis networks are highlighted by showing that intra-company connections can only achieve a maximum freshwater savings of 17% with significantly higher unit cost (+45%). Finally, the values of symbiosis connectivity index in the Pareto front correspond to higher freshwater savings, indicating the significant role of symbiosis network in the industrial park under study. This is the first study, where all the above elements have been taken into account simultaneously for the design of a water reuse network.

Keywords: wastewater treatment, water scarcity, membranes, circular economy, mixed integer nonlinear programming, water network integration
1. Introduction

Water demand for the manufacturing industry, which currently accounts for 5% of global freshwater uptake, is expected to increase by 400% by 2050, mostly in emerging countries (United Nations World Water Assessment Programme, 2015). However, only a small percentage of the water uptake by industries is contained in the products and the rest is either lost (e.g. evaporation, leaks) or discharged as wastewater effluent (Asano et al., 2007). Moreover, industrial discharges, if not treated adequately, can severely affect the quality of water resources, even when collected by a public sewer system and to a municipal wastewater treatment plant (European Environment Agency, 2018). Therefore, efficient use of water is essential for sustainable growth of industries and can play an important role in reducing regional and global water stress (Flörke et al., 2013).

Many industrial processes, particularly non-potable applications such as boilers and cooling systems, can use alternative sources of water rather than freshwater. The most readily available water sources are recycled and reused discharges from various unit processes either directly or after appropriate level of treatment (Asano et al., 2007). Yet, most manufacturing industries heavily rely on drinking quality water through private or municipal water supply due to the high immediate costs associated to establishment and operation of water reuse systems. However, it is argued that water reuse in industry brings not only environmental benefits such as reduction of freshwater intake and pollution discharge, but also long-term economic benefits to the participating companies (Chertow and Lombardi, 2005).

The main direct economic benefit is cost reduction for end-of-pipe effluent treatment before discharge due to ever increasing environmental restrictions, while long-term benefits are increased reliability of the water supply and reduced dependency on freshwater supply (Chertow and Lombardi, 2005). Water efficiency in industry is particularly relevant for countries with developing and emerging economies, which face more pressing water-related challenges due to climate change, poor infrastructure and failure in providing reliable water supply to the growing population and industry (Flörke et al., 2013; Seckler et al., 1999).

Traditionally, the effort in water reuse has been towards closing the loop within individual industries. Instead, cross-industry (or industrial symbiosis) networks have developed in the last decades (Lieder
and Rashid, 2016). In industrial symbiosis, industries located in geographical proximity of other industries, for example in an industrial park, can exchange water with each other and reduce their freshwater intake. One of the successful examples of industrial symbiosis is located in Kalundborg, Denmark (Jacobsen, 2008). The development of the network began when the region faced groundwater scarcity due to increase in industrial activities in the 1960s. The network further evolved over more than four decades to include exchange of water, energy and material between up to eight public and private companies. As in Kalundborg, industrial symbiosis is under constant growth, whether existing industries expand or new industries form. The development of Kalundborg symbiosis started as a spontaneous evolution through mutual exchanges, whereas most industrial parks are now created through planned incremental growth (Park et al., 2008). Therefore, design of symbiotic exchange networks needs to consider the long-term growth in industrial parks, particularly in emerging countries, which are under constant industrial developments. More importantly, the dynamic design should consider the projected water scarcity to evaluate the significance of water saving solutions in the long-term.

Mathematical optimization is often used to develop decision-making tools and study the technical feasibility of industrial symbiosis solutions. In case of water reuse, numerous studies have proposed optimization frameworks for network synthesis and design for intra- and interplant water network integration. Jęzowski (Jęzowski, 2010) provides a comprehensive review and survey of methods applied in literature. General deterministic mathematical formulations of the water integration network optimization problem in the form of non-convex mixed integer nonlinear programming (MINLP) are presented in various studies (Ahmetović and Grossmann, 2011; Alnouri et al., 2015; Chen et al., 2010; Chew et al., 2008; Galán-Martín et al., 2015; Karuppiah and Grossmann, 2008; Khor et al., 2012; Kim, 2012; Rubio-Castro et al., 2010). Non-convex MINLP problems are complex, and in order to handle the combined difficulty of non-convexity and integrality, mathematical programming approaches rely on techniques such as presolving, convexification, linear outer approximations and repeated division of the feasible domain, to name a few (Bussieck and Vigerske, 2010; Ruiz and Grossmann, 2017). Nevertheless, despite the significant algorithmic advances, realistically sized
MINLPs remain computationally demanding, which limits the research on solving water network synthesis problems in their general form (Jeżowski, 2010).

One of the most common simplifications is to consider the investigated systems as static and only focus on current or end-of-life demand. However, designing water symbiosis networks involves large investments in piping and treatment units and needs appropriate planning for network upgrades. Therefore, in order to provide a long-term sustainable solution, it is crucial to utilize prior knowledge on future developments in the water network optimization problem. Accommodating future network expansions requires an incremental multi-level optimization problem formulation over a certain period to find which water connections and treatment units to consider and in what sequence to ensure that the solution at each level is close to the overall optimum without compromising the solutions in the later stages (Hartline, 2008). The incremental approach is able to consider influencing internal and external factors such as demand growth and availability of resources in determining optimal solutions at different stages of network design. The practical importance of the incremental design approach is illustrated by several recent operational research studies related to budgeting or network expansion (Baxter et al., 2014; Hartline and Sharp, 2006; Kalinowski et al., 2015). However, we have found few recent studies in water network synthesis that have considered a so-called “multi-period” optimization approach (Bishnu et al., 2014; Leong et al., 2016; Liu et al., 2017; Sotelo-Pichardo et al., 2014). Bishnu et al. (2014) was the first study that addressed the necessity of using multi-period approach in water network reuse design using the general deterministic MINLP formulation. However, the study only considered direct water reuse with no treatment. Sotelo-Pichardo et al. (2014) included centralized treatment units in the multi-period formulation using an initialization approach for the MINLP problem formulation to reduce the computation time. Leong et al. (2016) formulated a multi-period problem for synthesizing direct water reuse for cooling systems considering short-term changes in market demand and plant-shot-down schedule. Liu et al. (2017) used centralized treatment units in the MINLP formulation for long-term planning of water reuse network in an industrial park. Centralized treatments can significantly limit the reuse potential, particularly in industrial parks with various effluents, whereas decentralized “fit-for-purpose” treatment technologies, despite of their
potentially higher cost, can provide flexible and adaptive solutions for water reuse networks that are under constant development.

Multi-objective analysis of deterministic MINLP formulations has been done for economic and environmental objectives in various studies such as in supply chain management (Grossmann and Guillén-Gosálbez, 2010; Hugo and Pistikopoulos, 2005) and heat exchanger networks (Onishi et al., 2017; Yee and Grossmann, 1990). However, to the best of our knowledge, there is no study that has performed a rigorous multi-objective evaluation of water network synthesis using multi-level incremental optimization with prior knowledge.

Based on the above mentioned gaps, the novelty of this study lies in: i) developing a deterministic multi-level incremental optimization framework for water network synthesis, ii) including prior knowledge of demand growth and projected water scarcity, , iii) incorporating a comprehensive formulation of water network synthesis problem including multiple pollutant and different treatment units and iv) performing a multi-objective optimization of the network including freshwater savings and the relative cost of network structure in terms of connections and treatment units. This is the first time that all the four aspects mentioned above are simultaneously addressed in an actual large-scale water network integration problem. We applied the incremental framework to the Ruaraka industrial park in Kenya including various unit processes. Moreover, the significance of having a water symbiosis network so as to minimize the freshwater intake in Ruaraka industrial park was investigated by introducing a symbiosis connectivity index.

2. Material and Methods

2.1 Case study

2.1.1 Description of the industrial park

Ruaraka industrial park located in Nairobi (Kenya) is a core pilot case in the Danish Strategic Sector Cooperation project in Kenya and therefore was selected as our case study for the synthesis of a water symbiosis network. The industrial park consists of various manufacturing companies, each having multiple unit processes with low to high water consumption. The Ruaraka region faces serious
freshwater availability issues. The municipal water supply infrastructure is poor and can barely meet the increasing water demands of the industries collated in Ruaraka industrial park and the surrounding settlements. As a result, industries have been acquiring private boreholes and extensively abstracting groundwater, which has caused a significant decline in groundwater levels and water quality. To mitigate the impact of industrial activities on the water scarcity problem in the Ruaraka region in the coming years, design of a water symbiosis network is proposed. To investigate the water symbiosis potentials, five companies in Ruaraka with the highest non-potable water intake that were willing to participate in the study are selected (Figure 1). For confidentiality reasons, the exact nature of the companies cannot be revealed. Each company participates with one to three non-potable water consuming unit processes categorized in four groups:

1. boiler feed water (medium pressure)
2. cooling makeup water (closed loop system)
3. process water (e.g. paper production, chemicals)
4. service water (e.g. laundry, washing, and transport)

**Figure 1.** Overview of five companies in Ruaraka industrial park (Kenya) selected for this study
Table 1 shows the data collected or estimated from the selected companies in Ruaraka. The data on flow includes water demand and water loss. Each unit process can be potentially both a receiver and a sender of water.

2.1.2 Water pollution parameters

To define water quality, we used two conventional aggregated parameters to simplify the water quality analysis and keep the generality of the problem formulation for treatment and reuse:

- Chemical Oxygen Demand (COD)
- Total Dissolved Solids (TDS)

COD and TDS mainly account for physical and bio-chemical properties of water and wastewater. COD is an indication of the total quantity of organic pollutants that are present in various forms in wastewater. The effect of using water containing high COD in industrial process systems can be significant. The particulate COD fractions can create deposits and the biodegradable fractions can favour microbial growth and result in biofouling (Asano et al., 2007). TDS is a measure of the total amount of organic and inorganic dissolved and colloidal pollutants in wastewater. The adverse effect of high TDS content in water include corrosion, foaming and process interference (Asano et al., 2007).

The water quality requirements in terms of average values of COD and TDS for each unit process, as well as the contributions in increasing the concentration of COD and TDS after water reuse are listed in Table 1. We note that we have not included input uncertainty in this study (see section 3.5). Therefore, the variabilities of flow and water quality values (in terms of standard deviation) are not shown.

Table 1. Data collected or estimated for the selected companies in Ruaraka industrial park

<table>
<thead>
<tr>
<th>Company</th>
<th>Unit process</th>
<th>Flow</th>
<th>Water quality requirement</th>
<th>Pollution increase after use</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Water</td>
<td>Flow</td>
<td>COD↑</td>
</tr>
</tbody>
</table>
### Table 3: Chemical oxygen demand, COD in freshwater

<table>
<thead>
<tr>
<th></th>
<th>demand</th>
<th>loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m³/h</td>
<td>%</td>
</tr>
<tr>
<td>A</td>
<td>(1) 200</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>(2) 70</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>(4) 70</td>
<td>5</td>
</tr>
<tr>
<td>B</td>
<td>(2) 7</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>(4) 17</td>
<td>20</td>
</tr>
<tr>
<td>C</td>
<td>(1) 50</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>(3) 40</td>
<td>10</td>
</tr>
<tr>
<td>D</td>
<td>(2) 9</td>
<td>5</td>
</tr>
<tr>
<td>E</td>
<td>(1) 7</td>
<td>10</td>
</tr>
</tbody>
</table>

2. Based on 2019 data
3. Chemical oxygen demand, COD in freshwater is assumed 10 mg/l
4. Total dissolved solids, TDS in freshwater is assumed 500 mg/l

#### 2.1.3 Water treatment units

The main elements of a water symbiosis network are the piping segments and treatment units. We included decentralized treatment units in the problem formulation, which treat each stream individually before being reused in other processes. In this study, two different membrane technologies are considered:

1) Ultra filtration (UF)
2) Reverse osmosis (RO) in combination with UF

The treatment configurations, treatment efficiencies with regards to COD and TSS removal, and water recovery are given in Table 3.

The two above-mentioned technologies have different treatment efficiency and water recovery (see Table 2). UF membranes require relatively low pressure and are primarily used to remove particulate pollutants (Fane, 1996). High pressure RO membranes systems are mainly used to remove dissolved pollutants and require pre-treatments (e.g. by using UF membranes) to reduce potential fouling (Jiang et al., 2017). As also shown in Table 2, a treatment system with higher removal efficiency has a lower
This conflicting feature increases the complexity of the problem in finding the optimum water saving solutions.

Table 2. The characteristics of treatment configurations used in this study as decentralized treatment in the water symbiosis network.

<table>
<thead>
<tr>
<th>Treatment configuration</th>
<th>Treatment efficiency</th>
<th>Water recovery</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%COD</td>
<td>%TDS</td>
<td>%Flow</td>
</tr>
<tr>
<td>UF</td>
<td>45</td>
<td>23</td>
<td>85</td>
</tr>
<tr>
<td>UF + RO</td>
<td>70</td>
<td>97</td>
<td>45</td>
</tr>
</tbody>
</table>

Another interesting aspect of using membrane treatment units in incremental network optimization is the flexibility of the membrane configurations due to their modular nature. In this case study, UF treatment units could be expanded and used as pre-treatment to the RO systems.

2.2 Optimization framework

In this section, we first present the comprehensive mathematical formulation of standard single-level of water network synthesis problem in the form of MINLP including multiple pollutants and different treatment units. Afterwards, we present the incremental extension of the problem with prior knowledge, which is the main contribution of this study. We implemented the MINLP model with the incremental extension in the open-source Julia language (Bezanson et al., 2017) using JuMP optimization package (Dunning et al., 2017). We then directly solved the large-scale MINLP problem for the presented case study to global optimality using the open source general-purpose global optimization solver SCIP (Achterberg, 2009).
2.2.1 General problem formulation (single-level)

The network under study consists of a known number of the water consuming unit processes with given water demand and maximum allowed concentration of pollutants in the inlet. They can receive water from a freshwater resource or reuse water from the outlet of other unit processes. Water for reuse can be treated through a combination of different decentralized “fit-for-purpose” treatment units. Water contamination after use in each unit process is considered as given increase in the concentration of pollutants. It is assuming that the possible internal recycling in each unit process is already in place and therefore is not included in the optimization problem. Water losses in the system are considered in unit processes and in the decentralized treatment units. The contamination and water loss values are listed in Table 1.

The problem is formulated as a standard nonconvex MINLP problem including mass balances for water and pollutants for each unit process, and binary variables for selection of water connections and treatment technologies. The nonlinearity and non-convexity of the model stems from bilinear terms in the constraints. Our implementation includes some modification in the constraints as compared to the standard formulations in literature (see Ahmetoví et al., 2015). In the formulation, recirculating restriction are imposed i.e. unit processes cannot send and receive water to and from the same unit process at the same time. It is also assumed that limited recirculation is already implemented in some unit processes before exiting the unit –e.g. cooling systems or cascade washing– and therefore no internal recirculation in unit processes is considered. Figure 2 shows the superstructure of the water reuse network. The full list of variables and parameters, as well as the equations for mass and flow balances and the other constraints are given in detail in the supplementary information (SI), S1.
Figure 2. Superstructure of a standard single-level water network with multiple pollutants and different decentralized treatment units. In this study, the single-level formulation is further extended to incremental formulation with prior knowledge.

2.2.2 Multi-objective optimization

Since the industrial park under study is located in a water stress region, the primary objective is to minimize the total freshwater intake by treating and reusing water between unit processes inside and across industries:

$$\min \sum_{i=1}^{NP} q_i^{FW}$$  \hspace{1cm} (2.1)

where $NP$ is the total number of unit processes considered in the optimization problem. and $q_i^{FW}$ is freshwater intake by unit process $i$.

The cost of the water symbiosis network is an important factor influencing the optimum design. Therefore, we included a secondary objective to reflect the relative cost contribution of the water network elements in terms of piping and treatment cost:
\[
\min \sum_{i=1}^{NP} \sum_{j=1}^{NP} q_{ij}^{RT} d_{ij} f^P + \sum_{i=1}^{NP} \sum_{j=1}^{NP} q_{ij}^{R} \left( \sum_{m=1}^{NT} y_{ijm}^R f_m^T \right)
\]  

(2.2)

**Table 3** Relative cost contribution factors assumed for the network elements

<table>
<thead>
<tr>
<th>Elements</th>
<th>Relative cost factor (f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe segment (100 m)</td>
<td>0.5</td>
</tr>
<tr>
<td>UF</td>
<td>5</td>
</tr>
<tr>
<td>UF + RO</td>
<td>20</td>
</tr>
</tbody>
</table>

We applied this simple but efficient factor-based approach for our preliminary study as an alternative to more detailed economic evaluations of treatment technologies in literature (Garrido-Baserba et al., 2018; Vanrolleghem et al., 1996). This simplification was introduced as a consequence of the complications involved in calculating detailed economic factors in the context of emerging countries as well as rapid market developments for advanced membrane technologies. This approach allows for a generalized multi-objective analysis for the two conflicting primary and secondary objectives of minimizing freshwater intake and the relative cost of network, respectively.
The “ε-constraint” technique (Mavrotas, 2009) is applied for multi-objective optimization in order to generate a set of Pareto solutions. It consists of implementing the secondary objective (2.2) as an inequality constraint subject to a range of ε-values and solving the problem of minimizing freshwater intake (2.1).

2.2.3 Incremental extension (multi-level)

The general formulation of the network presented as a single-level standard MINLP problem in section 2.2.1 is further extended to enable incremental multi-level optimization with prior knowledge. The purpose of the incremental approach is to find a sequence of feasible solutions, one per level (or period), such that later solutions build upon prior solutions. The incremental optimization shares similarities with online problems with the main difference that online optimization is based on no knowledge of future inputs, whereas incremental approach requires full knowledge of the input sequence (Hartline and Sharp, 2006). In other words, the online optimization entails solving the optimization problem at single levels by building on the existing solutions, while the incremental optimization involves solving at all the levels at the same time.

Given the general problem formulation described earlier and in SI (S1), we define the incremental formulation as follow:

**Incremental set:** $l \in NL$ is the set of indices for incremental optimization levels.

**Incremental variables:** For set and variable definitions used in constrains please refer to the general (single-level) formulation and in SI (S1). All the variables defined in the single-level problem will have an additional dimension accounting for value of the variables at each incremental level.

**Incremental objective function:** Contrary to single-level problems, where the goal is to minimize one objective value, the objective of an incremental extension must be an appropriate representation of objectives of individual levels written as a single expression. There are several variation of such a representation, the ratio and sum ones being the most common (Hartline, 2008). In this study, we used the weighted sum approach to be able to evaluate the cumulative performance of the network. We were then able to include different weighing factors reflecting the severity of water scarcity at each
level when defining the incremental scenario (see Section 2.3). The possibility of using weighted sum has also been addressed Bishnu et al. (2014) The objective is to minimize the cumulative freshwater intake over the planning period. Thus, the formulation of the incremental objective function is as following:

\[ \text{Obj}^{inc} = \sum_{i=1}^{NL} \omega_i \text{Obj}_i \]  \hfill (2.4)

where \( \text{Obj}^{inc} \) is the primary incremental objective function, \( \text{Obj}_i \) is the primary objective of each incremental level, \( \omega_i \) is the weight used for each level. In this study, the weights correspond to the water scarcity factors at each level.

**Incremental constraints:** The constrained secondary objective related to the relative cost of network (eq. 2.2) is further expanded to calculate the cumulative relative network cost of all the three levels. The incremental formulation requires a monotonicity constraint, i.e. the feasible solutions at each level should be part of feasible solutions of all following levels. In other words, if a network element is active in the solution of one level, it must remain active in solutions of all subsequent levels. The following constraints are considered to ensure the monotonicity of the solutions at each incremental level:

\[ x_{ijl} \leq x_{ij(l+1)} \]  \hfill (2.5)

\[ q_{ijl}^{RT} = q_{ij(l+1)}^{RT} x_{ijl} \]  \hfill (2.6)

\[ y_{ij1l}^{R} = y_{ij1(l+1)}^{R} + y_{ij2(l+1)}^{R} \]  \hfill (2.7)

\[ y_{ij2l}^{R} = y_{ij2(l+1)}^{R} \]  \hfill (2.8)

where \( x_{ijl} \) is the binary variable for the existence of connections and \( q_{ijl}^{RT} \) is the water flow after treatment between unit processes \( i \) and \( j \) at level \( l \). \( y^{R} \) is a binary variable for choosing treatment units for each connection in each incremental level.
Constraint (2.5) ensures that the same connections from the previous level exist in the next level in addition to new connections. Since each connection represents a piped flow, constraints (2.6) restrict the existing flow between two unit processes at each level \(^{(q|f^R)_{i,t}}\) to be the same in the consequent levels. The purpose is to not remove but add new pipe connections at each level. We assumed that only one piping connection can exist between two unit processes.

Constraints (2.7) and (2.8) guarantee that the treatment configuration chosen at the previous level is only expanded and not being replaced. In the present case study, constraint (2.7) allows expansion of the UF treatment system with RO membranes, whereas constraint (2.8) guarantees that if RO is selected, it is not removed as the network expands.

2.3 Description of the incremental scenario

We defined a three-level incremental scenario for the case study in Ruaraka. The total duration is 9 years and each level is 3 years long. The scenario includes projection of water demand growth and water scarcity. The scenario details for the selected companies in Ruaraka Park are described below and summarized in Table 4.

2.3.1 Water demand growth factor

We considered a three-level hypothetical water demand growth scenario, as following:

- **Company A:** Increase in water demand by a factor of 1.5 at Level 3.
- **Company B:** Joining in period 2, increase in water demand by a factor of 2 at Level 3.
- **Company C:** Increase in water demand by a factor of 2 at Level 2.
- **Company D:** Constant demand.
- **Company E:** Increase in water demand by a factor of 1.5 at Level 3.

2.3.2 Freshwater scarcity factor

As previously mentioned, the industrial park under study is located in a water stressed region with a poor and unreliable water supply as well as decreasing ground water availability. Therefore, we have
introduced a three-level water scarcity factor to reflect the increasing importance of water saving in the long-term. We estimated that the water scarcity factors would double in each period based on the increase in the numbers of private boreholes and depth of such boreholes established by the companies in the last 20 years.

**Table 4.** The 3-level incremental scenario defined for water demand growth and freshwater scarcity

<table>
<thead>
<tr>
<th>Water demand growth factor</th>
<th>Current</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company A</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>Company B</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Company C</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Company D</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Company E</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Freshwater scarcity factor</th>
<th>Current</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>For all companies</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

### 2.4 Symbiosis connectivity index

For further evaluation of the symbiosis network, the degree of cross-company connections is quantified by introducing a symbiosis connectivity index (SCI). SCI is defined based on the clustering coefficient for special networks, where the number of observed links in a network is divided by the number of possible directed links in the completely connected network (Barthélemy, 2011):

\[
SCI = \frac{\sum_{i=1}^{NP} \sum_{j=1}^{NP} x_{ij} DN_{ij}}{NP (NP - 1)}
\]  

(2.3)

where \(x_{ij}\) are the binary variables defining existence of connections between unit processes \(i\) and \(j\). \(DN\) is a binary matrix (adjacency matrix), where entries corresponding to zero for potential intra-company connections, and all other entries are one. \(NP\) is the total number of unit processes.

Even though SCI does not consider the real quality and weight of the connections, it is a useful measure to demonstrate how the network builds up incrementally.
3. Results and Discussion

In this section, we present the results of applying incremental optimization with prior knowledge for the design of a water symbiosis network for the selected companies in Ruaraka industrial park and discuss the findings.

The problem formulation contains 981 variables (318 binary, 663 continuous) and 1192 constraints. It was solved with 0.05 optimality tolerance and 0.001 feasibility tolerance using the open source SCIP Optimization Suite 7.0 (Gamrath et al., 2020). The CPU time for the calculations was at worse 11000 seconds on a High Performance Computing (HPC) server operating at 2.60GHz.

3.1 Impact of prior knowledge

Firstly, we investigated the impact of including a prior knowledge in the incremental optimization approach by comparing the results with ones from the online approach with no prior knowledge. The comparison was done on the results from the single-objective problem of minimizing freshwater intake. The optimization outcomes are summarized in Table 5. The cumulative freshwater savings achieved by online optimization with no prior knowledge (26%) is about the same as with incremental optimization (25%), whereas the resulted relative unit cost is 19% higher (36.4) as compared to the incremental optimization with prior knowledge (29.4). Figure 3 shows the comparison for minimum freshwater intake and the resulting relative unit cost of network per cubic meter of freshwater saved at each level. We observe that the case of online optimization with no prior knowledge has a higher freshwater savings in Level 1 (123.4 m$^3$/h) with a consequently higher unit cost of 37.9. However, the freshwater savings in Level 2 and 3 are lower than the case of incremental optimization with prior knowledge, whereas the unit cost remains higher. This indicates that an online optimization with no prior knowledge overdesigned the network with much higher cost (+37%) in Level 1, and as a result, compromised the higher freshwater savings with lower unit cost that could be achieved in Level 2 and 3 when including prior knowledge. In other words, the incremental approach with prior knowledge gives a significant advantage in providing a more flexible and expandable network for later stages without compromising the network cost. This could not be the case for the network obtained by online
optimization with no prior knowledge, where most of the savings are exploited at early stages and
might limit the more beneficial expansions in the near future. Therefore, we note the importance of
investigating the impact of prior knowledge in incremental design in the early planning stage. The
concern for overdesigning at early stage of network design is also addressed by other studies (e.g.
Leong et al., 2016; Sotelo-Pichardo et al., 2014) but was not investigated as compared to the case with
no prior knowledge. One can also argue that the impact of incremental optimization is more significant
in the case of more heterogeneous industrial parks with many irregular developments. Whereas in a
single industry or a group of industries, where all unit process expand proportionally, the practical
significance of the incremental approach with prior knowledge is limited.

**Table 5.** Outcome of online and incremental optimization of the water symbiosis network under study
at three levels

<table>
<thead>
<tr>
<th></th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freshwater demand (m³/h)</td>
<td>446</td>
<td>564</td>
<td>588</td>
<td>1597</td>
</tr>
<tr>
<td><strong>Online (with no prior knowledge)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freshwater savings (m³/h)</td>
<td>123.4</td>
<td>147.6</td>
<td>147.6</td>
<td>418.5</td>
</tr>
<tr>
<td>Freshwater savings %</td>
<td>27%</td>
<td>25%</td>
<td>24%</td>
<td>26%</td>
</tr>
<tr>
<td>Total relative network cost</td>
<td>4671.0</td>
<td>5283.4</td>
<td>5283.4</td>
<td>15237.8</td>
</tr>
<tr>
<td>Relative network cost per m³ saved</td>
<td>37.9</td>
<td>35.8</td>
<td>35.8</td>
<td>36.4</td>
</tr>
<tr>
<td><strong>Incremental (with prior knowledge)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freshwater savings (m³/h)</td>
<td>76.9</td>
<td>152.0</td>
<td>162.4</td>
<td>391.4</td>
</tr>
<tr>
<td>Freshwater savings %</td>
<td>17%</td>
<td>26%</td>
<td>27%</td>
<td>25%</td>
</tr>
<tr>
<td>Total relative network cost</td>
<td>1845.8</td>
<td>4713.3</td>
<td>5015.5</td>
<td>11574.6</td>
</tr>
<tr>
<td>Relative network cost per m³ saved</td>
<td>24.0</td>
<td>31.0</td>
<td>30.9</td>
<td>29.6</td>
</tr>
</tbody>
</table>
Figure 3. Comparing the results of optimization with or without prior knowledge of future developments for the freshwater saved (a) and the resulted relative unit cost of network per cubic meter of freshwater saved (b) with the objective of minimizing overall freshwater intake.

Figure 4 shows the details of the water symbiosis network matrix obtained by the incremental optimization with prior knowledge to achieve maximum fresh water savings. The results are presented as separate exchange matrices for each incremental level with water senders in rows and water receivers in columns. The water flow rate exchanged (in m$^3$/h) is indicated only for Level 3, denoting flow rates after treatment considering water losses during treatment. The overall maximum possible water savings among the selected companies is 25% by expanding the network incrementally under the three-phase planned growth. The optimum water network design for Level 1 achieves 17% freshwater savings and more under-developed as compared to Levels 2 and 3, with 27% and 28% savings, respectively. As mentioned earlier, it implies that an overdesign of the network in Level 1 could compromise the savings in Level 2 and 3 provided by the water demand growth and therefore is not exploited by the optimization algorithm. The incremental development of symbiosis network is further discussed in section 3.4.
Figure 4. Matrix of Water symbiosis network obtained via three-level multi-objective incremental optimization to achieve maximum freshwater savings (25%). Each cell represents a water flow in m$^3$/h from water sender (rows) to water receivers (columns). Different colours for each matrix cell indicate the level of treatment for each connection. Water flows are rounded values in m$^3$/hr (minimum 2 m$^3$/hr). The coloured cells in level 1 and 2 have the same flow rates as the ones indicated in the level 3 matrix. Empty cells indicate no water exchange and white cells indicate no treatment.

3.2 Multi-objective analysis

As stated earlier, the primary objective of this study was to find the solution(s) leading to the highest water savings through symbiotic connections based on single-objective optimization, as presented in section 3.1. However, the practical application of synthesising a water symbiosis network requires a systematic evaluation of the trade-off between relative network cost and water saving potential. Therefore, we performed a multi-objective optimization for freshwater intake and network cost minimization by generating a partial Pareto front using the “ε-constraint” technique. The total relative
network cost preference was implemented as an inequality constraint with varying maximum targeted values.

Figure 5 provides a graphical representation of the Pareto front. The Pareto set values are listed in Table S2 in SI. The primary and secondary objectives (cumulative freshwater intake and cumulative relative network cost) are converted to the percentage of water intake and relative unit cost of network for a cubic meter of freshwater saved, respectively. The Pareto-front demonstrates a knee point at 86% overall freshwater intake (or 14% freshwater savings) with the relative unit cost of 15.3 as a balanced solution hereafter the relative unit cost of cubic meter freshwater increases more rapidly. It means that if the decision makers are aiming at reducing the freshwater intake more that 14%, they would need to do it at much higher unit cost. Notably, the Pareto front in Figure 5 does not appear to be convex towards the end range of cost, indicating that savings do not always have a direct relation with the cost towards reaching the overall maximum water saving capacity of 25%. The non-convexity of the Pareto front is also confirmed by the irregular variation of the freshwater savings obtained for each incremental level (Figure 5b).

**Figure 5.** Graphical representation of the Pareto front generated for the primary and secondary objectives (a) and the obtained savings in freshwater intake for each incremental level (b)

Figure 6 shows the optimum water symbiosis network suggested by the multi-objective optimization considering the trade-off between freshwater savings and relative network cost. The optimum design results in a reasonable saving of 14% with a much lower relative unit cost of 15.3 as compared to the
network presented in section 3.1 to achieve maximum freshwater saving of 25\% with relative unit cost of 29.6. As expected, the network with the optimum design is less developed as compared to the solution for maximum freshwater savings presented in Figure 3. This means that the more expensive RO system is less used and the connections are mainly limited to the neighbouring companies. For example, company A is the main sender of water to all the companies to achieve maximum freshwater savings (see Figure 4), using mainly the combination of UF and RO treatment solutions. On the other hand, the optimum network (Figure 6) suggests that company A sends less water with less treatment to companies B and C only. Also, the smaller water streams from companies D and E to company B is eliminated in the optimum design to avoid the highcost of piping and treatment.

The results presented in this section illustrate the benefit of multi-objective analysis incorporating economic and environmental concerns as decision-making objectives. The Pareto approach can clearly demonstrate the trade-off between freshwater savings and network cost in designing water reuse networks. Even though the focus of this study is on designing water reuse network for industrial parks that face increase in water demand and water scarcity, we also addressed the compromise that a more exploited network can have on the overall network cost to achieve more freshwater savings.
Figure 6. Water symbiosis network matrix with optimum design obtained via three-level multi-objective incremental optimization to achieve freshwater savings of 14% and relative unit cost of 15.3. Details are explained in Figure 4.

3.3 Significance of symbiosis connections

To investigate the significance of cross-company symbiotic water exchange for freshwater savings, we compared the results presented in section 3.1 for maximum freshwater savings to the case with no symbiosis connections (i.e. only intra-company water reuse). For the no-symbiosis case, we set the corresponding epsilon for piping cost to zero to exclude cross-company piping connections in the optimization formulation. The optimization outcomes are summarized in Table 6.

Figure 7 shows the water savings at each level for both cases of with and without symbiosis connections. The incremental effect is shown in the case with symbiosis connections, whereas the no-symbiosis case has very low network development. The difference is particularly evident in the last
incremental level with the highest water scarcity factor, where the symbiosis results in more efficient
exploitation of the water saving potential. Level 1 has similar freshwater savings in both with and
without symbiosis, as a compromise made to have higher water savings in the subsequent levels that
have higher water scarcity factor in the symbiosis case. The no symbiosis case did not achieve major
additional savings in Level 2 and 3 as the network is limited to few intra-company solutions. More
importantly, the no symbiosis case resulted in an overall freshwater savings of 17% with the relative
unit cost of 42.9 (see Table 6), which is a much higher cost per saving achieved as compared to the
symbiosis network with 25% freshwater savings and 29.6 relative unit cost (see Table 5). This means
that a single industry would have a much higher treatment cost to save freshwater, as compared to a
collective of industries exchanging water for reuse.

The results presented in this section demonstrate the advantages of combining intra- and symbiosis
connections in achieving higher freshwater savings with lower unit cost as compared to only intra-
company connections (no-symbiosis) for the case of Ruarka industrial park. These results bring the
attention not only to the environmental benefits of industrial symbiosis in reducing freshwater intake,
but also the potential economic benefits of exchanging water for reuse from neighbouring industries at
a lower cost that using internal streams that might need more extensive treatment.

Table 6. Outcome of 3-level incremental optimization including no symbiosis connections

<table>
<thead>
<tr>
<th></th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freshwater savings m³/h</td>
<td>88.3</td>
<td>88.3</td>
<td>99.6</td>
<td>276.3</td>
</tr>
<tr>
<td>Freshwater savings %</td>
<td>20%</td>
<td>16%</td>
<td>17%</td>
<td>17%</td>
</tr>
<tr>
<td>Total relative network cost</td>
<td>3925.4</td>
<td>3925.4</td>
<td>3991.9</td>
<td>11842.6</td>
</tr>
<tr>
<td>Relative network cost per m³ saved</td>
<td>37.9</td>
<td>35.8</td>
<td>35.8</td>
<td>42.9</td>
</tr>
</tbody>
</table>
**Figure 7** The maximum freshwater savings achieved for each incremental level with and without symbiosis network.

3.4 Development of symbiosis connections

Figure 8 illustrates the incremental development of the symbiosis network for achieving maximum freshwater savings (based on results in section 3.1 and 3.2). The values of symbiosis connectivity index, SCI (equation 2.3) are indicated at each stage of development. In Level 1, where the demand and the water scarcity factor are the lowest, more intra-company connections are exploited. The main developments are in Level 2 and 3, with higher demand and water scarcity factors. Figure 8b shows the SCI values corresponding the Pareto set of solutions presented in Figure 5. The general trend in SCI values suggest that symbiosis network expansion increases freshwater saving potentials. However, as the freshwater savings approach the maximum capacity, higher SCI values do not necessarily translate to significantly higher freshwater savings. These results can thus support decision makers in considering the trade-off between water savings and symbiosis network connectivity as an indication of network complexity.
Figure 8 (a) Incremental development of the water symbiosis network (intra-company connections are not shown) for maximum freshwater savings based on a 3-level scenario of growth in demand and water scarcity. Symbiosis connectivity index (SCI) values are indicated at each stage of development. (b) Symbiosis connectivity index (SCI) values corresponding to the freshwater savings at each incremental level based on the Pareto front presented in 5. For a more clear demonstration, the SCI values in each level in (a) are highlighted in (b) as red marks.
3.5 General discussion on the proposed approach and research prospects

The presented incremental optimization approach was developed as a large-MINLP formulation of water network synthesis with multiple pollutants and treatment units, and multi-objectives. More importantly, the framework was able to incorporate prior knowledge on water demand growth and projected water scarcity for the preliminary design of in industrial parks. This approach, which for the first time incorporates all the above aspects, can be further applied to (i) other network types, such as energy and materials, and (ii) other scenarios, including budgeting for network implementation, where the intermediate solutions that have the risk of becoming permanent solutions are close to the overall optimum. This is especially relevant in the context of developing and emerging countries, with constraints in available resources.

The present study does not address the uncertainty in the input data for long-term design of water symbiosis networks. Therefore, it is necessary to generate models that can incorporate the uncertainty in prior knowledge. Other studies have addressed uncertainty only in single-level water network synthesis (Hung and Kim, 2011; Karuppiah and Grossmann, 2008; Zhang et al., 2009) and highlighted the importance of considering process and input uncertainty in designing water reuse networks. In case of vague uncertainties with no clear probability distributions, fuzzy optimization methods could be applied (Pishvaee and Razmi, 2012).

Life cycle assessment (LCA) and life cycle cost (LCC) analysis have been successfully integrated in various optimization studies to design sustainable chemical processes (Guillen-Gosalbez et al., 2008; Muñoz et al., 2018; Portha et al., 2010). The same analysis needs to be integrated in optimizing the design of a water symbiosis network in order to evaluate the detailed environmental and economic impacts. This is particularly important, when dealing with various treatment technologies that contribute to the environmental and economic factors differently based on their emissions, chemical usage and the generated reject water/sludge for disposal.

The circular economy agenda attracts use and recovery of all resources. Even though water remains a critical resource, particularly in developing and emerging countries, there is a new interest in recovering other valuable resources available in industrial wastewater streams (e.g. chemicals, metals).
Wastewater streams generated from different industrial activities have been traditionally characterized based on their environmental impacts (European Environment Agency, 2018). However, industrial water reuse requires a more specific categorization to take into account the resource recovery potentials besides the effect on the product quality or the efficiency of processes.

4. Conclusions

In this study, we evaluated the symbiotic water saving potentials in an industrial park in Kenya under planned growth and projected water scarcity. The main findings of this study are:

- Developing a comprehensive incremental optimization framework with prior knowledge for a large scale water network synthesis in the form of MINLP including multiple pollutants and different treatment units.

- Illustrating the significance of incorporating prior knowledge in designing water symbiosis network to prevent an overdesign of network with high costs in the early stage and help achieve a more flexible and expandable network with lower relative unit cost in the long term. In the case of Ruaraka industrial park, the incremental optimization approach with prior knowledge results in a network with similar maximum freshwater savings (25%) but 19% lower unit cost as compared to the network with no prior knowledge.

- Performing a systematic multi-objective analysis for freshwater saving and relative unit cost for treatment and piping. The multi-objective analysis for Ruaraka industrial park suggests an optimum network design to achieve 14% freshwater savings with about half unit cost as compared to the network design for maximum freshwater savings.

- Illustrating the advantage of symbiosis connections as compared to the no symbiosis connections (i.e. only intra-company connections) in achieving maximum freshwater savings with lower unit cost. In case of Ruaraka, the network with no symbiosis obtained an overall 17% maximum freshwater savings with significantly higher (+45%) unit cost as compared to the symbiosis solution.
• Evaluating the incremental development of symbiosis connections through the introduced symbiosis connectivity index (SCI) values. The corresponding SCI values obtained from the multi-objective analysis of the network under study suggest that the expansion of the symbiosis network will result in higher freshwater savings throughout the Pareto front at each incremental level. However, as the network approaches its maximum savings capacity, the SCI values do not necessarily correlate directly with higher freshwater savings. This indicates that expanding the network beyond its optimum design might not result in significantly higher savings as it gets closer to the maximum saving capacity.

• The research prospects for the presented incremental approach with prior knowledge of input data in the optimization of water reuse network include: i) incorporating uncertainty in the input data, ii) integrating LCA and LCC analysis in optimization, and iii) more focus on industrial wastewater characteristics for including resource recovery solutions.

5. Acknowledgements

The authors gratefully acknowledge the funding provided by the Danish International Development Agency (DANIDA) to conduct this study as part of Gecko project (Green and Circular Innovation for Kenyan Companies) through Grant number 17-M05-DTU and ERASE project (Evaluation of Resource recovery Alternatives in South African water) through Grant number 18-M09-DTU.

6. Software availability

The implementations of this study is done in open source platforms and can be shared upon request.

7. References


https://doi.org/10.1007/s12532-008-0001-1


https://doi.org/10.1016/S0011-9164(96)00085-9


Onishi, V.C., Ravagnani, M.A.S.S., Jiménez, L., Caballero, J.A., 2017. Multi-objective synthesis of work and


