Process intergration: Cooling water systems design

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Abstract

Cooling water systems use equipments such as cooling towers to remove waste heat from the process to the atmosphere. Heat exchanger networks are generally designed with a set of heat exchangers arranged in parallel. This design means that all heat exchangers receive cooling water at the same supply temperature and the outlet streams are mixed before being returned to the cooling tower. This arrangement results in higher cooling water flowrate and low cooling water return temperature thus reducing cooling tower efficiency.

Previous research on cooling water systems has focused mainly on heat exchanger network thus excluding the interaction between heat exchanger network and the cooling towers. Majozi and Moodley (2008) developed a technique for simultaneous targeting and design in cooling water systems comprising at least two cooling towers. Their work excluded the performance of the cooling tower. Kim and Smith (2001) developed a methodology for grass root design of cooling water system with one cooling source taking into account the cooling tower performance. Penjeshahi and coworkers (2009) also developed a similar methodology using advanced pinch design. The last 2 contributions were only limited to one cooling source.

This paper presents a technique for grassroot design of cooling water system for wastewater minimization which incorporates the performances of the cooling towers involved. The study focuses mainly on cooling systems consisting of multiple cooling towers that supply a common set of heat exchangers. The heat exchanger network is synthesized using the mathematical optimization technique. This technique is based on superstructure in which all opportunities for cooling water reuse are explored. The cooling tower model is used to predict the thermal performance of the cooling towers. Two case studies are presented to illustrate the proposed technique. The first case results in a nonlinear program (NLP) formulation and the second case yields mixed integer nonlinear program (MINLP). In both cases the cooling towers operating capacity were debottlenecked without compromising the heat duties.

1 Introduction

Industrial development and other economic activities have led to an increase in freshwater consumption and contamination of freshwater resources. One of the major water using operations in industries is the cooling water systems. Cooling water systems use equipments such as cooling towers to remove waste heat from the process to the atmosphere. These systems also generate wastewater through the blowdown mechanisms. Escalating costs of waste treatment, stricter environmental regulations on industrial effluent and scarce water resources have led to studies which concern various means of minimizing water usage and waste generation.

Previous research on cooling water systems has focused mainly on minimizing water usage by optimizing heat exchanger networks. The common tool used in this regard was pinch analysis developed by Linnhoff and co-workers in the early 80's. This technique was adopted for mass exchanger network design (El-Halwagi & Manousiouthakis, 1990) and later developed into WaterPinch™ (Wang & Smith, 1994). Few authors used mathematical optimization techniques to design the heat exchanger networks (Majozi & Moodley, 2008; Kim & Smith, 2003; Panjeshahi *et. al.,* 2009). This technique was first used by Takama and co-workers (1980) for wastewater minimization and was adopted directly for heat integration.

The synthesis of cooling water systems which takes into consideration the interaction between heat exchanger network and the cooling towers has not been fully explored. The following section gives a brief overview of developments in this regard.

1.1 Cooling water system design: mathematical optimization techniques

Takama *et al.* (1980) were first to use mathematical programming for targeting and designing water using networks in the refinery. This technique involved superstructure in which all possible network features were explored. The possible features included recycles and reuse as shown in Figure 1. The superstructure was optimized subject to material and energy balances at each node and across each unit. The strength of this technique lies in its ability to handle many practical constraints, e.g. forced or forbidden matches, capital cost functions, control and safety constraints.

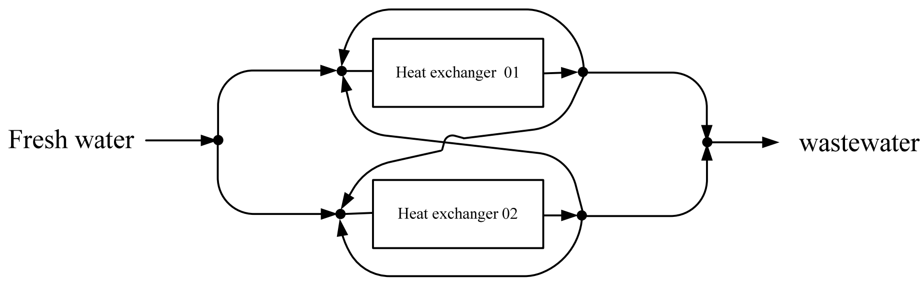

Figure 1 The superstructure for water using network

Kim and Smith (2003), Majozi and Moodley (2008) and Teles *et al.* (2009) solved the problems of cooling water using networks through mathematical optimization techniques. The formulated problems were generally nonconvex NLP (Majozi & Moodley, 2008; Teles *et al.,* 2009) or MINLP)(Kim & Smith, 2003; Majozi & Moodley, 2008). Optimization of nonlinear problem generally yields a local optimum solution depending on the starting point. Thus it is important to best initialize the problem.

1.2 Cooling tower model

The prediction of cooling tower thermal performance dates back to 1925 by Merkel. Bernier (2004) and Kröger (2004) applied Merkel's theory to develop the cooling tower model. Bernier (1994) evaluated the cooling tower thermal performance by deriving a one dimensional model based on the thermal behavior of water droplet in a spray type cooling tower. The model was able to predict the cooling tower outlet temperature and change in air humidity.

The model used in this paper was developed by Kröger (2004) by considering a control volume as shown Figure 2.

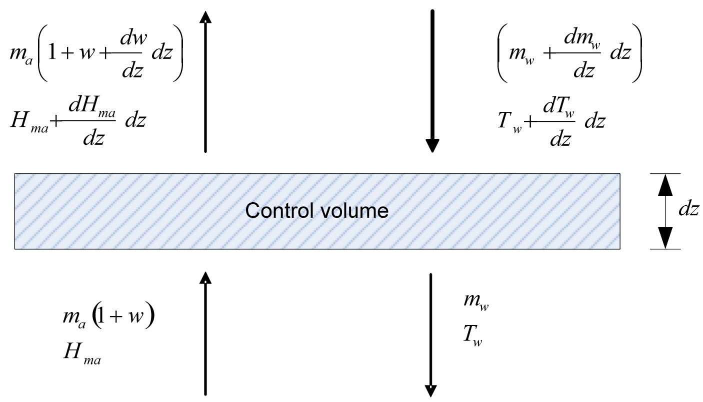

Figure 2 Control volume

The governing equations that predict the thermal performance of a cooling tower are given by Equations (1), (2) and (3). Equations (1) and (2) define the mass and energy balance for the control volume, respectively. Equation (3) defines the air enthalpy change for the control volume.

$$\frac{dm_w}{dz} = m_a \frac{dw}{dz} \tag{1}$$

$$\frac{dT_w}{dz} = \frac{m_a}{cp_w m_w}\left(\frac{1}{cp_w}\frac{dH_a}{dz} - T_w \frac{dw}{dz}\right) \tag{2}$$

$$\frac{dH_a}{dz} = \frac{Ka_{fi}A_{fi}}{m_a}\left(Le_f(H_{as} - H_a) + (1 - Le_f)H_v(w_s - w)\right) \tag{3}$$

In Equations (3) a_{fi} is the wetted area divided by the corresponding volume of the fill and A_{fr} is a frontal area. The Lewis factor, Le_f, appearing in Equation (3) is the relationship between the heat-transfer coefficient and the mass-transfer coefficient, i.e. $\frac{h}{Kc_{pma}} = Le_f$.

This paper presents a technique for grassroot design of cooling water system which incorporates the performances of the cooling towers involved. The study focuses mainly on cooling systems consisting of multiple cooling towers that supply a common set of heat exchangers. The heat exchanger network is synthesized using the mathematical optimization technique. The cooling tower model is used to predict the thermal performance of the cooling towers whilst taking the thermal conditions of the associated heat exchanger network into account.

2 Cooling water systems model development

The cooling water system consists of cooling towers and heat exchanger network. Therefore the mathematical model for designing cooling system entails the heat exchanger network model and the cooling tower model. The heat exchanger model entails a superstructure in which all possible cooling water reuse opportunities are explored. The mathematical optimization formulation was developed from the superstructure given in Figure 3 by considering energy and mass balance equations across each cooling water using operation and at each node. The optimum heat exchanger network design is found by minimizing the cooling tower inlet flowrates. The interaction between the heat exchanger network and the cooling towers is investigated using the cooling tower model derived by Kröger (2004).

The heat exchanger network model is based on the following two possible practical cases.

Case I. Specified maximum cooling water return temperature to the cooling tower without a dedicated source or sink for any cooling water using operation. This situation arises when packing material inside the cooling tower is sensitive to temperature and any cooling tower can supply any water using operation whilst the water using operation can return to any cooling tower.

Case II. Specified maximum cooling water return temperature to the cooling tower with a dedicated source or sink for any cooling water using operation. This is similar to Case I except that the geographic constraints are taken into account. A particular cooling tower can only supply a particular set of heat exchangers and these heat exchangers can only return water to the same supplier.

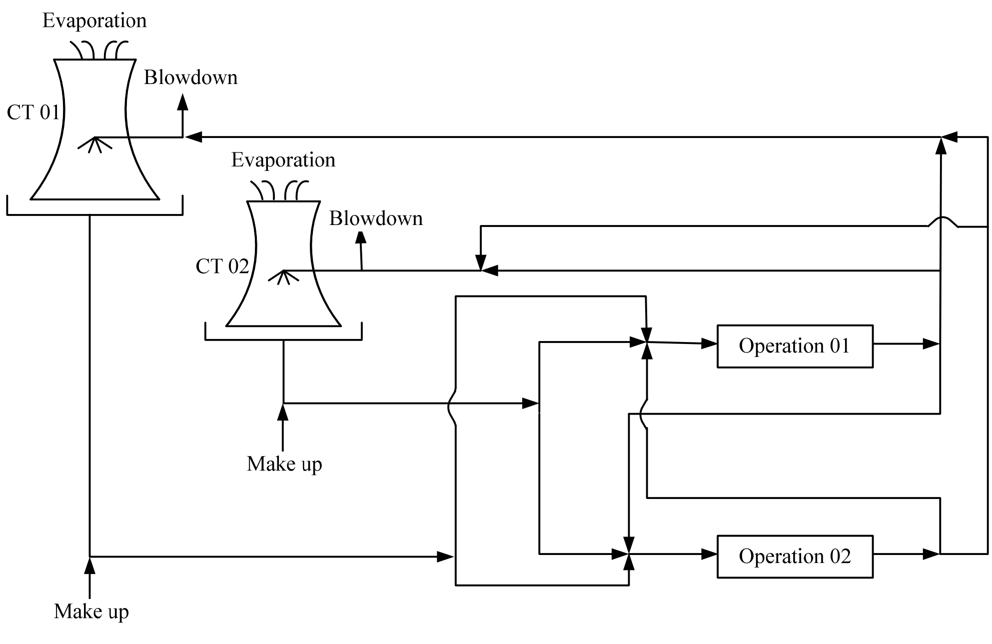

Figure 3 Superstructure for a cooling water system

3 Case studies

The application of the proposed technique is demonstrated by considering one example for Cases I and II. This example was extracted from the paper by Majozi and Moodley (2008).

The formulation for Case I consists of bilinear terms which are nonconvex thus rendering the model NLP. This model is difficult to initialize because the starting point might be infeasible or the solution might be locally optimum (Gololo & Majozi, 2010). To overcome these difficulties the technique proposed by Quesada and Grossmann (1995) was used to linearize the bilinear terms. This technique uses the upper and the lower bounds to create a convex space for the bilinear terms as shown in the next section. The formulation for Case II consists of binary variables and bilinear terms which are nonconvex. This renders the model MINLP (Gololo & Majozi, 2010). Similar to Case I, the model was linearized using the linearization relaxation procedure by Quesada and Grossmann (1995).

3.1 Base case

Cooling water system in Figure 4 shows a set of heat exchanger networks which are supplied by a set of cooling towers. Each cooling water using operation is supplied by freshwater from the cooling tower and return back to the cooling tower. The implication of these arrangements results in higher return cooling water flowrate and low return cooling water temperature thus reducing cooling tower efficiency (Bernier, 2004).

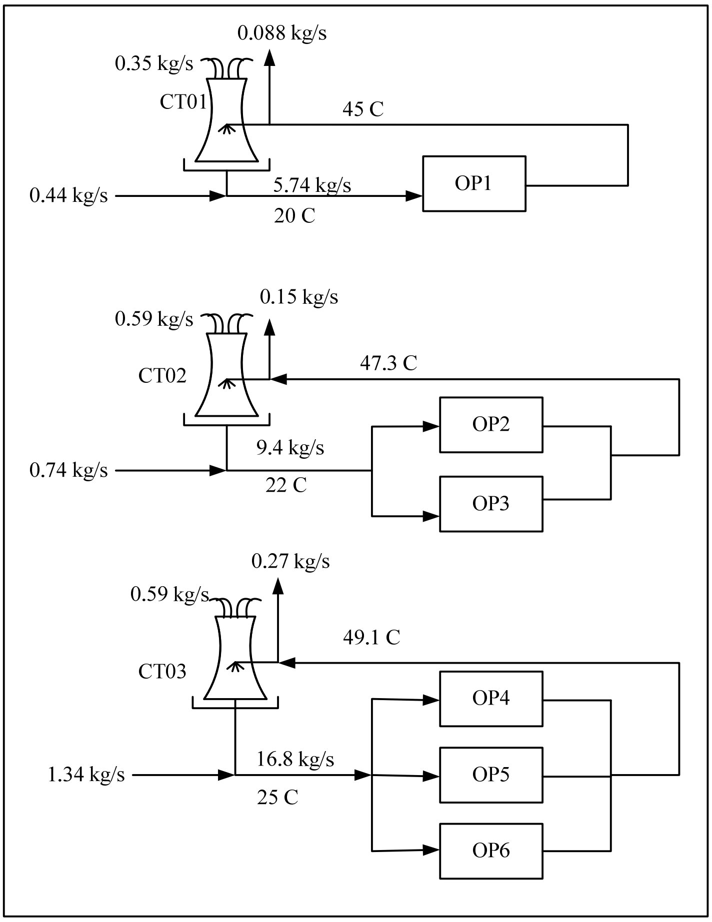

Figure 4 Base case (Majozi and Moodley, 2008)

3.2 Case I

In this case each cooling tower can supply any cooling water using operation. The return streams from any cooling water using operation can go to any cooling tower. The return temperature to any cooling tower is however specified.

Figure 5 shows the heat exchanger network after applying the methodology described above. By exploiting the opportunity for cooling water reuse, the overall circulating water decreased by 22 % and one cooling tower was eliminated. The cooling tower inlet temperatures are at their maximum values.

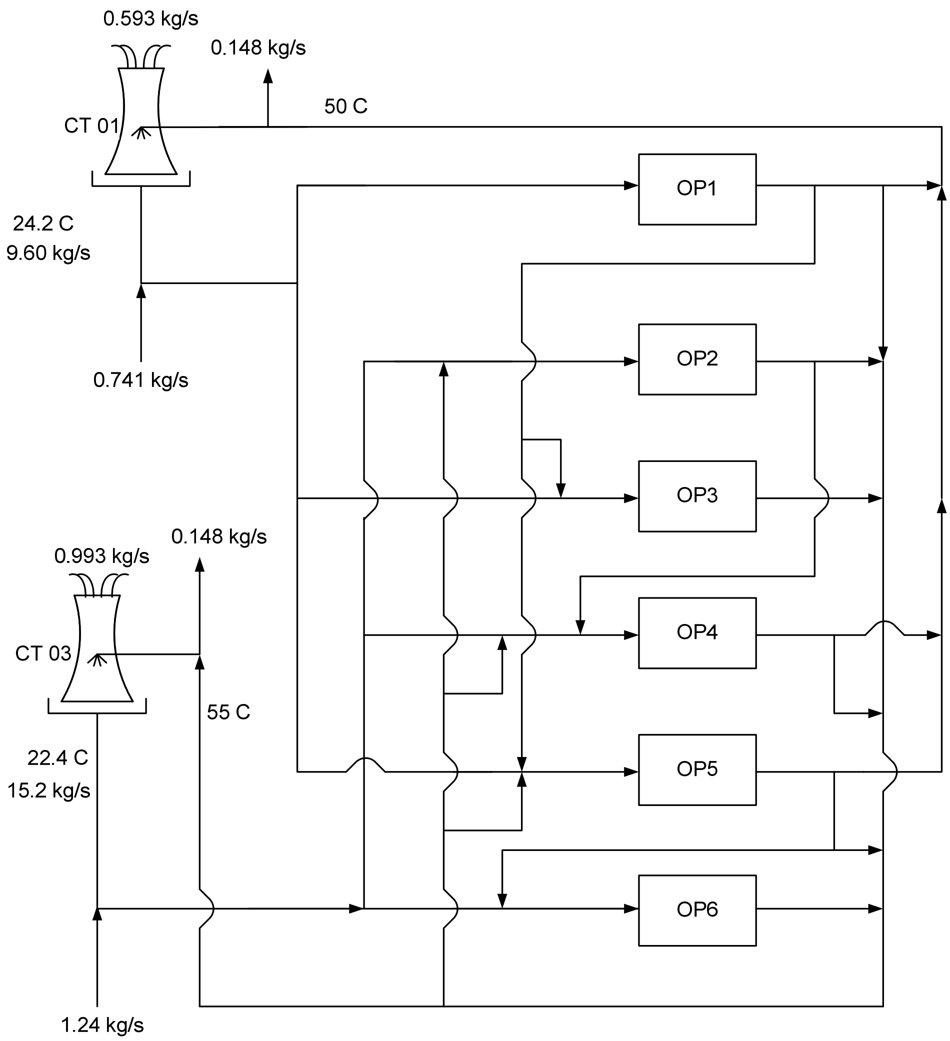

Figure 5 Final design of the cooling water system

These results show the opportunity to increase the heat duties, through expansions, without investing on a new cooling tower. The only additional investment required is on piping for reuse streams. For this case study the makeup and the blowdown was also decreased by 7%. However the decrease in makeup and blowdown cannot be guaranteed for all practical case studies and this is not the intended purpose in this study. The results summary are shown in Table 3.

Table 1 Results summary

Stream	base case(kg/s)	results(kg/s)
Make up	2.52	2.33
Blowdown	0.50	0.47
Circulating water	31.94	24.80

3.3 Case II

In this case a cooling tower can only supply a dedicated set of heat exchangers. This implies that each operation can only be supplied by one cooling tower. The return streams from any cooling water using operation can only go to its supplier cooling tower. The return temperatures to the cooling towers are also specified. Figure 7 shows the heat exchanger network after applying the methodology described above.

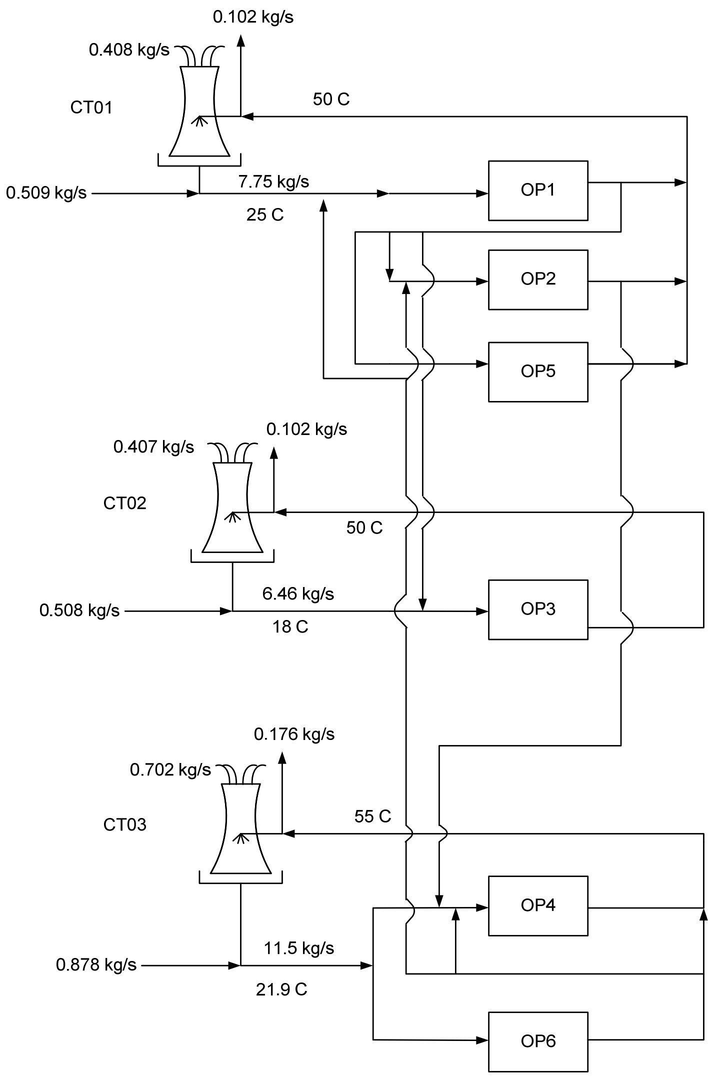

Figure 6 Final design of the cooling water system

By allowing for the cooling water reuse, the overall circulating water decreased by 20 %. as shown in Table 4. This will decrease the pumping power requirement for the circulating pump thus reducing the pumping cost. The cooling towers spare capacity is also increased giving opportunities for increased heat load without investing in a new cooling tower. To satisfy the required heat duties with the reduced flowrate, the return temperature to the cooling towers is increased to the maximum value. The makeup and the blowdown are also decreased by 4%. As abovementioned, the decrease in makeup and blowdown cannot be guaranteed for all practical case studies.

Table 2 Results summary

Stream	base case(kg/s)	results(kg/s)
Make up	2.52	2.41
Blowdown	0.50	0.48
Circulating water	31.94	25.69

4 Conclusions

The mathematical technique for cooling water system synthesis with multiple cooling towers has been presented. This technique is more holistic because it caters for the effect of cooling tower performance on heat exchanger network. The cooling tower thermal performance is predicted using the mathematical model. The results obtained using this technique are more practical, since all components of the cooling water system are included in the analysis.

The proposed technique has the advantage of debottlenecking the cooling towers, which implies that a given set of cooling towers can manage an increased heat load. Furthermore, the overall circulation water is also decreased with an added benefit of decreasing the overall power consumption of the circulating pumps. The overall cooling towers effectiveness was also improved. There is also a potential for the reduction of makeup and blowdown water flowrate. The proposed technique shows a potential for capital cost saving in grassroots and retrofit designs.

Nomenclature

a_{fi}	surface area per unit volume
A_{fr}	frontal area
c_p	specific heat capacity
CT	Cooling tower
F	Flowrate
H	Enthalpy
h	heat transfer coefficient
K	mass transfer coefficient
Le_f	Lewis factor
m	flowrate
T	temperature
V	volume
W	humidity
z	cooling tower height
ρ	density
η	efficiency
ε	effectiveness

a_d , d_{da} , ATD and b_{db} Cooling towers fill parameters

Subscripts:

a	air
c	cold
h	hot
ma	moist air
min	minimum
s	saturation
w	water
wb	wet bulb

References

1. Bernier, M.A. Cooling tower performance: Theory and experiments. *ASHRAE Transactions Research*, 100, 114-121, 1994.
2. El-halwagi, M.M., & Manousiouthakis, V. Automatic synthesis of mass-exchanger networks with single-component targets. *Chemical Engineering Science,* 45(9), 2813-2831, 1990.
3. Gololo, K.V., & Majozi, T. On Synthesis and Optimization of Cooling Water Systems with Multiple Cooling Towers. Paper submitted to *Industrial and Engineering Chemistry Research Journal,* 2010.
4. Wang, Y.P., & Smith, R. Wastewater minimization. *Chemical Engineering Science,* 49(7), 981-1006, 1994.
5. Kim, J.K., & Smith, R. Cooling water system design. *Chemical Engineering Science,* 56,3641-3658, 2001.
6. Kim, J.K., & Smith, R. Automated Retrofit Design of Cooling Water Systems. *AICHE,* 49(7), 1712-1730, 2003.
7. Kröger, D.G. Air-cooled heat exchangers and cooling towers: mass transfer and evaporative cooling. Penn Well Corporation, USA, 2004.
8. Majozi, T., & Moodley, A. Simultaneous targeting and design for cooling water systems with multiple cooling water supplies. *Computer and Chemical Engineering,* 32, 540-551, 2008.
9. Panjeshahi, M.H., Ataei, A., Gharaie, M., & Parand, R. Optimum design of cooling water systems for energy and water conservation. *Chemical Engineering Research and Design,* 87, 200-209, 2009.
10. Quesada, I., & Grossmann, I.E. Global optimization of bilinear process networks with multicomponent flows. *Computer and Chemical Engineering,* 19(12), 1219-1242, 1995.
11. Takama, N., Kuriyama, T., Shiroko, K., & Umeda, T. Optimal water allocation in a petroleum refinery. *Computer and Chemical Engineering*, 4, 251-258, 1980.
12. Teles, J.P., Castro, P.M., & Novais, Q.A. MILP-base initialization strategies for the optimal design of water-using networks. *Chemical Engineering Science,* 64, 3736-3752, 2009.