Development and testing of an optimisation model at selected Eskom sites for an integrated water solution

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1. INTRODUCTION

This is a consolidated account of both Phase 1 and Phase 2 of the project. Phase 1 is focused on integrated water and membrane network systems, whilst Phase 2 is dedicated to cooling water system design that is characterized by multiple cooling towers. A cooling water system, in the context of this investigation, refers to a cooling tower with its associated set of heat exchangers.
In Phase 1, the developed model was validated using Eskom Kriel Power Station. The choice of this 110 M*l*/day site was informed by the availability of data and willingness of personnel to give guidance on testing and implementation of results. Preliminary results have shown potential savings of more than 12% in freshwater use. This facility operates on a zero liquid effluent discharge philosophy. Consequently, no mention is made of wastewater savings.

As part of knowledge transfer, a workshop was conducted at Eskom College, Midrand, from 17 to 19 June 2014. The workshop was aimed at demonstrating the applications of process integration in water minimisation. Graphical and mathematical optimisation techniques were presented in sufficient detail. In particular, the attendees were taken through the entire thinking process that is necessary for identification of relevant streams for optimisation, as well as characterisation of streams into sources and sinks.

The developed model has been successfully tested and applied to Eskom Kriel Power Station. Various scenarios were explored and analysed as potential sources for the final design. The most outstanding among the scenarios involved the reuse of blowdown from one cooling tower to the other and yielded almost 12% savings in freshwater use. This scenario was discussed in detail with the plant personnel and proved to be feasible. In essence, this is currently happening in Lethabo.

Phase 2 is premised on the observation that cooling water systems are generally designed with a set of heat exchangers arranged in parallel. 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. This report presents a technique for grassroot design of cooling water system for wastewater minimisation 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 optimisation 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 resulted in nonlinear programming (NLP) formulation and the second case yield mixed integer nonlinear programming (MINLP). The nonlinearity in both cases is due to the bilinear terms present in the energy balance constraints. In both cases the cooling towers operating capacity were debottlenecked without compromising the heat duties. Unlike the results of the work conducted in Phase 1, this work (Phase 2) has not been applied in a real life industrial problem.

2. METHODOLOGY FOR WATER MINIMISATION

The first step in mathematical model formulation requires the identification of potential sources and sinks in the facility or process of interest. Water sources are those operations whose effluent is potentially usable in other operations within the facility. On the other hand, sinks are those operations which have the capacity to reuse water/effluent from other operations. The source and a sink need not necessarily be different operations. There are many operations in the chemical engineering context that qualify as both a source and a sink. A typical example is a cooling tower. In order to avoid accumulation of dissolved solids in a cooling tower, water needs to be blown down and freshwater supplied as makeup. During blowdown, the cooling tower is a source and during makeup it is a sink. In a situation where the generated effluent is partially reused in the same source, the term '*recycle*' is used instead of '*reuse*'.

Figure 1 illustrates the concept of sources and sinks in the presence of a regeneration system. The regeneration system could be a typical membrane unit, e.g. reverse osmosis, electrodialysis, etc., which is introduced to increase reuse/recycle potential for water through partial treatment. It is worth mentioning, however, that the option of a regeneration system was not considered in this particular project.

The second step in mathematical formulation involves identification of all contaminants in the facility. This is followed by indication of maximum degree of contamination allowed in each operation to assess reuse and recycle opportunities. These limiting concentrations constitute key parameters in the model. The other parameters are flowrates allowed into each operation.

Once the process has been analysed as aforementioned, a mathematical model is then formulated based on the superstructure in Figure 1 and mass balances.

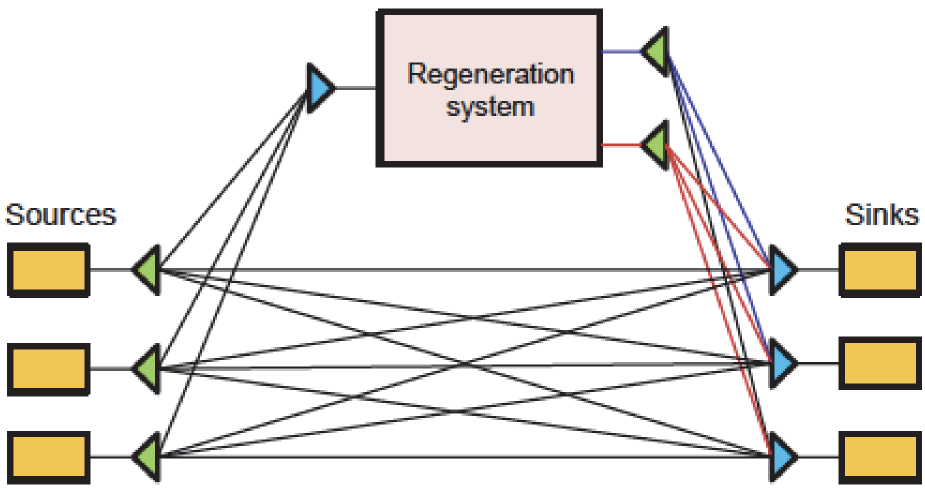

Figure 1. Typical network superstructure

2.1. Application of the Water Minimisation model: Eskom Kriel Power Station

2.1.1. Kriel Power Station background

Kriel Power station receives raw water from the Vaal and Usutu water schemes for various uses within the facility. Currently, Kriel Power Station exceeds its water consumption design target by 10 - 15 Ml/day on average. This equates to about 2.35 l/uso, where *uso* stands for units sent out in MWh. The target for the facility is to achieve 1.80 l/uso, hence this project.

In validating the model a use was made of the Kriel Power Station flowsheet as shown in Figure 2. The data for the flowsheet appear in Table 1 and Table 2. Table 1 shows stream characterisation into sources and sinks, which required in-depth understanding of the facility with the aid of personnel. As highlighted in the second interim report, a sink is an operation that receives water, whilst a source is an operation that generates usable water in the facility of interest. There are also units that qualify as both sources and sinks. A typical example in this regard is a cooling tower, which receives makeup water and generates blowdown. In both cases it acts as a sink and a source, respectively. Shown in Table 2 are stream flowrates which given by the Power Station personnel.

Table 1. *Characterisation of streams into sources and sinks*

Unit Operations	Sources	Sinks	Variables
Usutu Raw Water			X
Vaal raw water supply			X
Floor Washing		X	
3rd parties		X	
Sand filter backwash water		X	
Dirty Sand filter backwash water	X		
Power station potable water use (bathrooms, kitchen, etc.)		X	
Power station potable water leaking into drains	X		
Power Generation: Demin Water		X	
Power Generation: Demin Water to drains-mostly tank overflows	X		
Power Generation: CPP spent regenerants	X		
Ion Exchange: Spent regenerants	X		
Effluent Dam	X		
North Cooling Tower	X	X	
South Cooling Tower	X	X	
WWTW	X		
Ash Dam/Ash conditioning		X	
Dust suppression		X	
Vaalpan – mostly from leaks from process units	X		

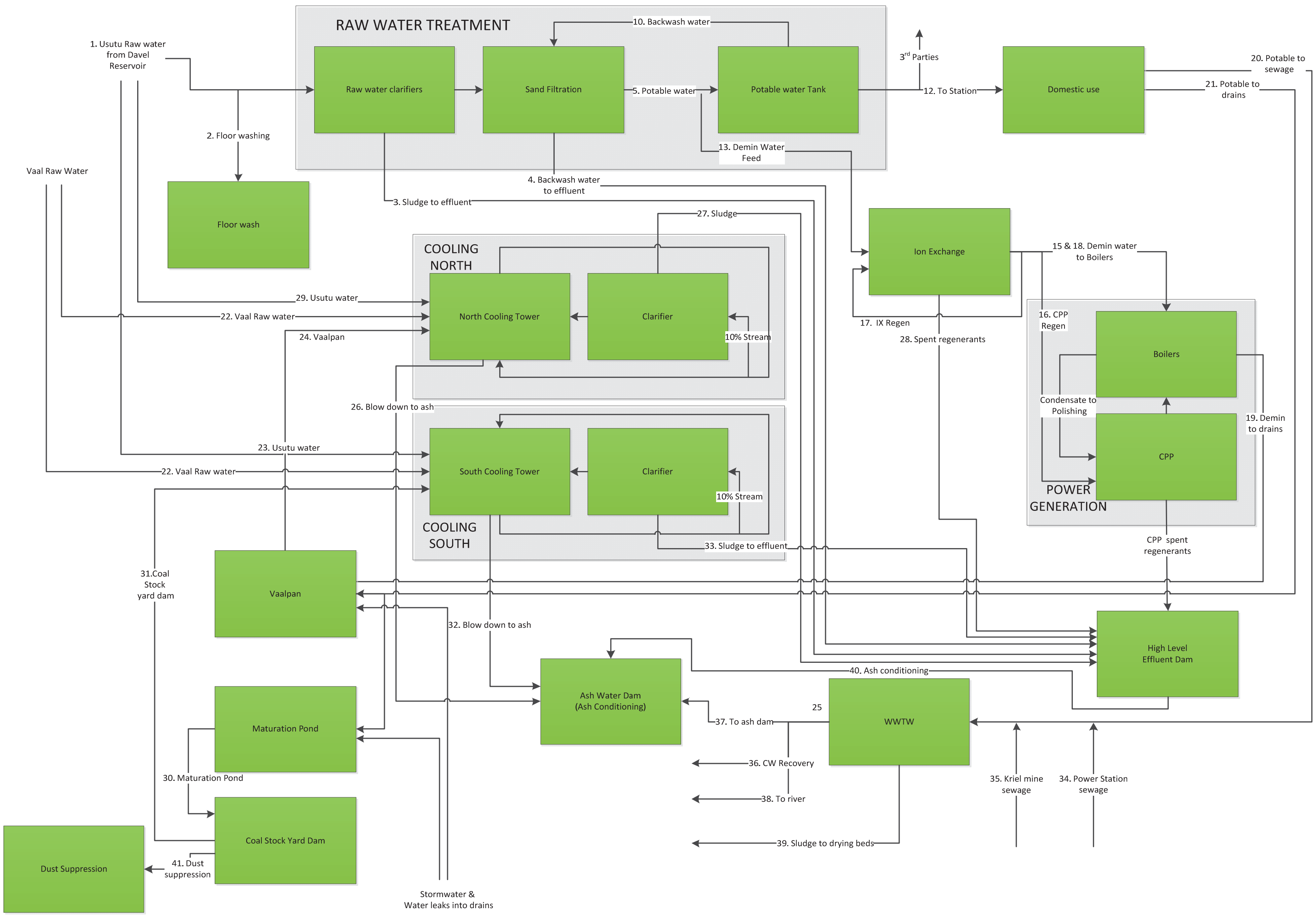

Figure 2. *Water network flowsheet for Kriel power station.*

Table 2. *Flowrates of identified streams*

		Flow rate	Stream quality	
Stream No	**Stream description**	**(m3/d)**	**TDS (mg/l)**	**Conductivity (uS/cm)**
1	Usutu Raw water from Davel Reservoir	14749	43	68.1
2	Floor washing (Fire-hydrants)	2203	43	68.1
3	Raw water clarifier sludge to effluent	444	61	**95**
4	Dirty backwash water to drains	444	48	**75**
5	Filtered water	14305	45	70.4
6 - 9, 11	Water 3rd parties		45	70.4
	Water to Kriel town		45	70.4
	Water to Kriel mine and NW Shaft		45	70.4
	Water to contractors		45	70.4
	Water to kwanala centre		45	70.4
	3rd parties	3000	45	70.4
10	Clean filter backwash water	444	45	70.4
12	Potable to Power Station	3000	45	70.4
13	Demin water feed	7862	45	70.4
14	Demineralized water production	7506	0	0.07
15	Demineralized water to Power Station	6824	0	0.07
16	Water to CPP regeneration	682	0	0.07
17	Deminiralized water to regeneration	682	0	0.07
18	HP Demineralized to Power Station by pump	0	0	0.07
19	Demin water to station drains	3412	0	0.07
20	Potable water to Sewage plant	300	255	400
21	Potable water to Station drains	1890	58	91
22	Vaal raw water supply	92778	130	204
23	Usutu Raw water to north cooling system	0	45	70.4
24	Recovered water from Vaalpan	800	732	1150
25	Recovered sewage effluent	1216	249	**391**
26	North cooling tower blow down	3177	2548	4000
27	North cooling tower clarifier sludge	714	2548	4000
28	Spent regenerants to effluent system	1039	127	**200**
29	Usutu raw water to south cooling system	0	45	70.4
30	Recovered water from the maturation pond	0	567	890
31	Recovered water fron coal stock yard	0	510	800
32	South cooling tower blow down	6467	2548	4000
33	South cooling tower clarifier sludge	627	2548	4000
34	Sewage from the Power Station	300	255	**400**
35	Sewage from the Kriel mine	1350	255	**400**
36	Sewage effluent for use in cooling	0	249	**391**
37	Sewage effluent to ash dams	0	249	**391**
38	Sewage effluent to the environment	0	249	**391**
39	Sewage sludge to drying beds	50	249	**391**
40	Ash conditioning	1400	6369	**10000**
41	Dust suppression	400	2548	**4000**

2.1.2. Results for the Kriel Power Station

Figure 3 shows the resultant flowsheet if the option of blowdown interchange is allowed between the north and south cooling towers. The freshwater target for this flowsheet is 96.55 Ml/day, which is about 12% savings in water. This target equates to about 2.1 l/uso, which is still higher that the design target of 1.8 l/uso.

Figure 4, on the other hand shows the flowsheet that corresponds to forbidding the option of reusing water from cooling tower to the other. Clearly, this amounts to reduction in degrees of freedom, which is concomitant with suboptimal results. This flowsheet corresponds to a target of 103.7 l/uso, which amounts to about 5.5% savings in freshwater use.

The results in Figure 3 and Figure 4 have been discussed with Eskom Kriel personnel and a final design is yet to be finalized.

2.2. Water Minimisation Conclusions

This report has addressed the synthesis of a water regeneration network that incorporates the detailed synthesis of an RON. The proposed model was applied to a literature case study and was then solved using GAMS/BARON in order to highlight its practicality. The results show that the use of multiple regenerators in the water network, can lead to a reduction in the total cost of the network due to the significant reduction in freshwater consumption and wastewater generation. It can also be concluded that, there is a significant benefit in allowing the removal ratio in the model to be a variable as this has severe significant on the cost and structure of the network. The implications of this study show that, detailed optimisation of regenerators within water networks can significantly improve wastewater management within process plants. Large computational times were however incurred due to the complex nature and structure of the model. It is also noteworthy that the proposed model was limited to one membrane technology. Multiple membrane technologies such as ultrafiltration can however be incorporated in the membrane network and thus offering a scope for future work.

The application of the model to a real life case study involving of the largest and complex power generation facilities in the country, Eskom Kriel Power Station, showed very promising results, with potential freshwater savings of 12% fully demonstrated and discussed with key personnel on site. However, this would only be feasible if blowdown interchange is allowed between the cooling towers. Elimination of this option yields less attractive results of about 6% savings in freshwater.

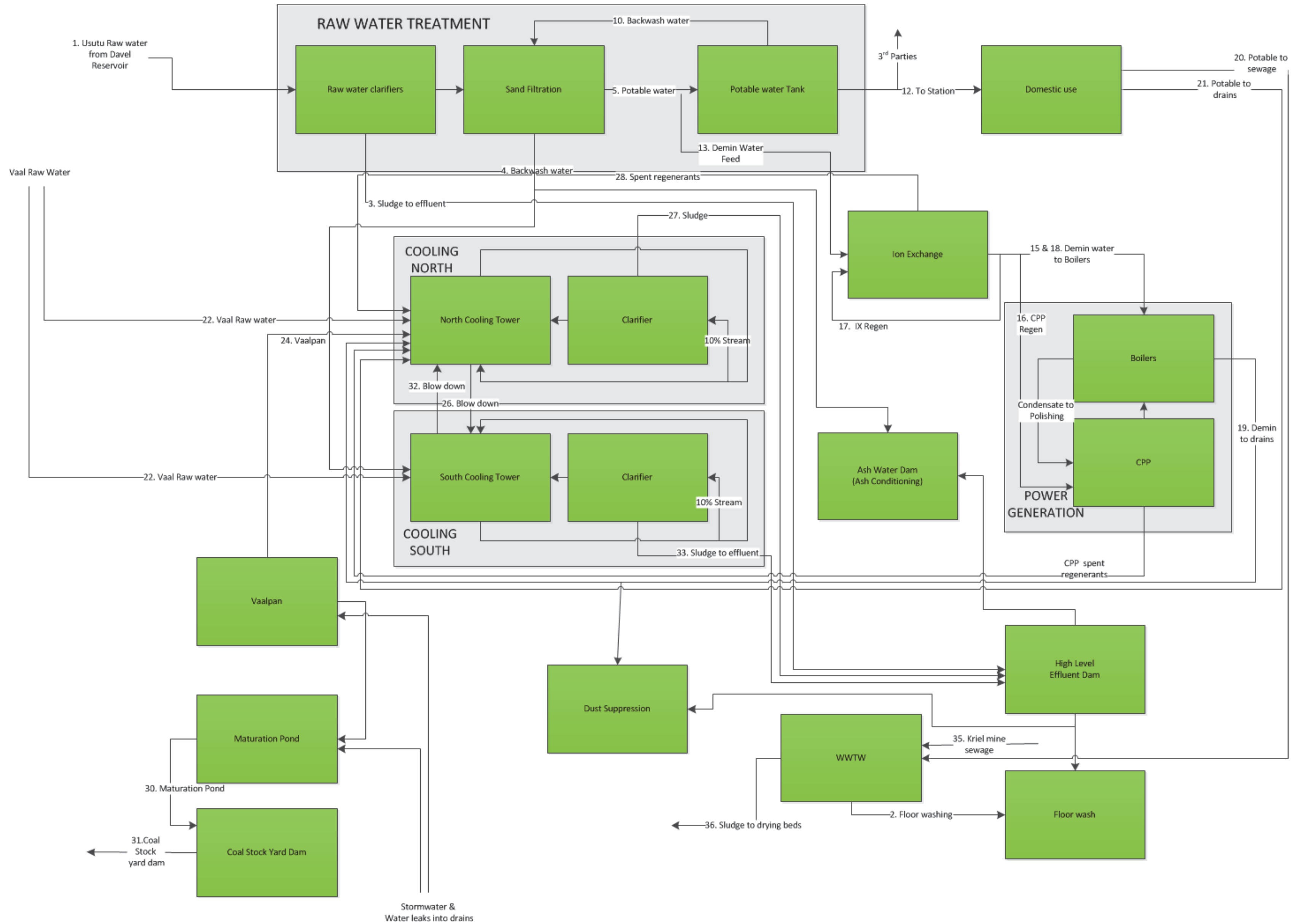

Figure 3. *Water network with the option of blowdown interchange.*

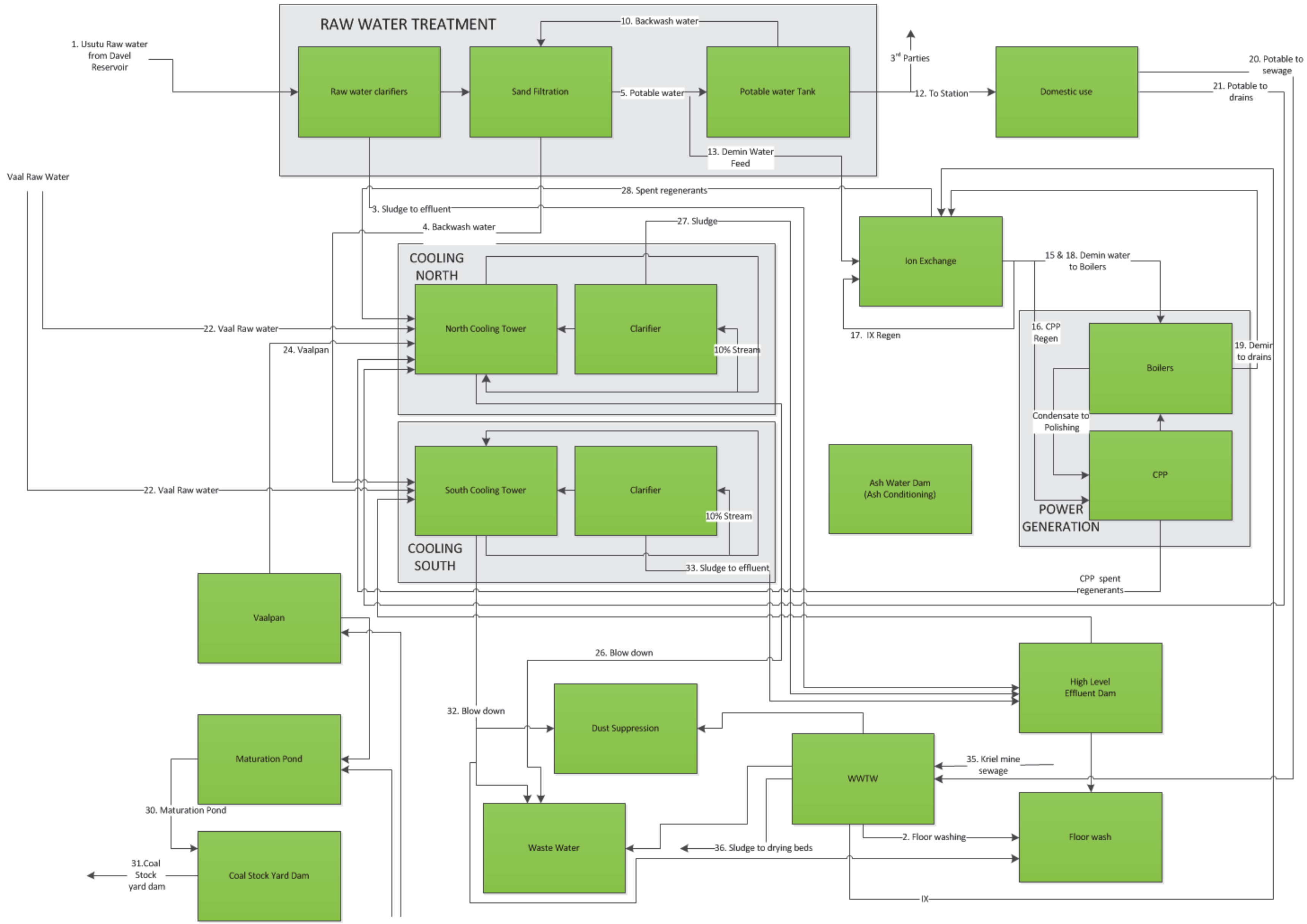

Figure 4. *Water network without the option of blowdown interchange.*

3. METHODOLOGY FOR COOLING WATER SYSTEM DESIGN

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 are explored. 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) by considering a control volume as shown in Figure 5.

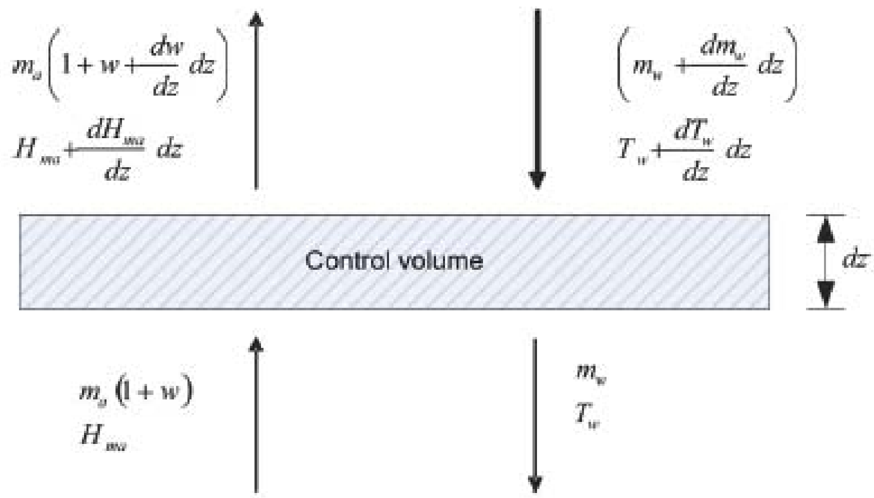

Figure 5. *Control volume*

The following assumptions were made:

- Interface water temperature is the same as the bulk temperature
- Air and water properties are the same at any horizontal cross section
- Heat and mass transfer area is identical

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 constrains 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.

Each of the cases entails the mass balance, energy balance and design constraints. The design constraints, in particular, cater for capacity limitations of both piping and equipment.

3.1. Mathematical formulation

The mathematical optimisation formulation is developed from the superstructure given in Figure 6 by considering energy and mass balance equations, as well as design constraints, across each cooling water using operation and at each node. Two cases that were considered are given in the following sections.

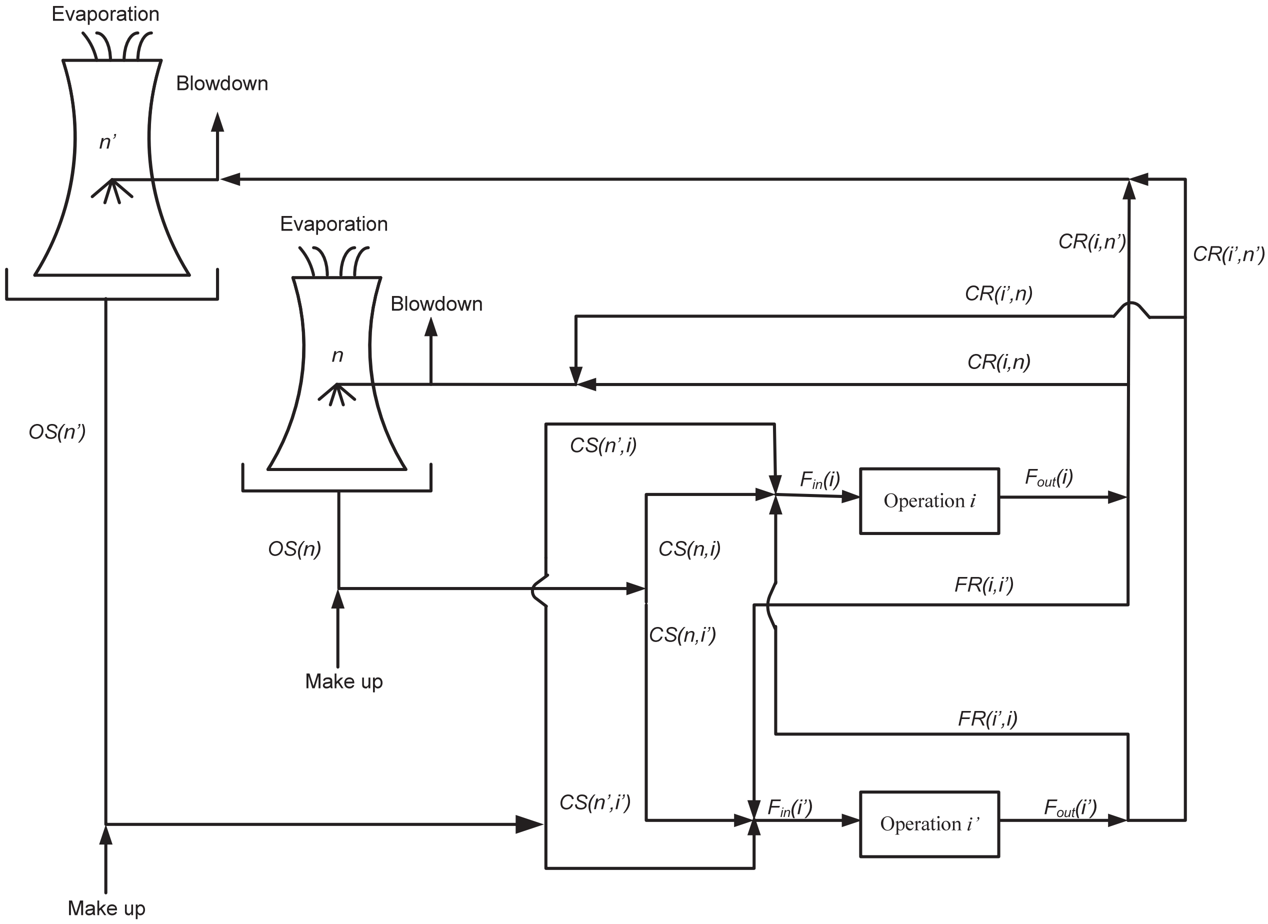

Figure 6. *Superstructure for a cooling water system*

3.1.1. A note on mathematical considerations: Reformulation Linearisation technique

It is worth mentioning at this point that the resulting mathematical model entails bilinear terms that render it nonlinear and inherently difficult to solve. The solution approach adopted in this work involved a Reformulation Linearisation technique to cast the model as a linear, hence convex, formulation with a global optimum. The solution obtained in this step is then used as the starting point for the exact (nonlinear) model. In most cases this approach significantly reduces computational effort and is likely to yield a globally optimum solution, if the bounds for the key variables are carefully selected. The following section gives a detailed account of the solution algorithm.

3.1.2. Solution algorithm

The solution procedure can be applied for both cases considered. The first step is to optimize the heat exchanger network model without the cooling towers. The results from the first iteration, which are cooling water return (CWR) temperatures and flowrates, become the input to the cooling tower models. Each cooling tower model then predicts the outlet water temperatures and flowrates. This is done by first assuming the outlet water temperature of a cooling tower. The assumption is done by subtracting 0.5 ^{o}C from the given cooling tower inlet temperature. The three governing mass and heat transfer equations are then solved numerically using fourth order Runge_Kutta method starting from the bottom of the cooling tower moving upwards at step size Δz. When the maximum height is reached, the temperature at this point will be compared with the CWR temperature. If the two agree within a specified tolerance, the cooling tower model will stop and the outlet temperature will be given as the assumed temperature, else the inlet temperature will be adjusted until the CWR temperature agrees with the calculated temperature.

The predicted outlet cooling tower temperatures and flowrates then become the input to the heat exchanger network model. If the outlet temperature of the cooling tower model agrees with the previous inlet temperature to the heat exchanger network model, the algorithm stops which implies that final results have been obtained. Otherwise the iteration continues. The solution algorithm flowchart is shown in Figure 7.

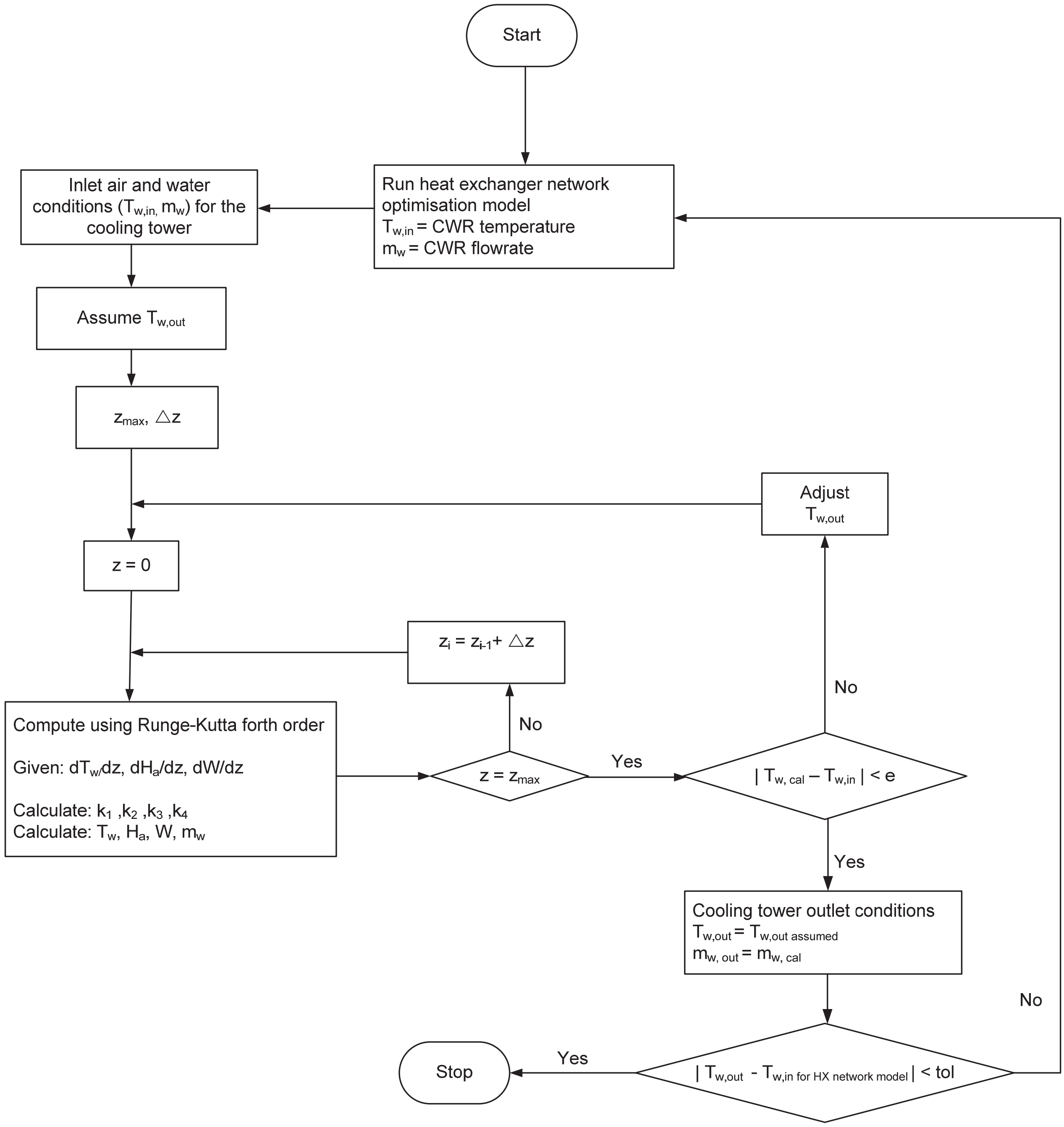

Figure 7. *Flowchart for cooling water system model*

3.2. 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 article by Majozi and Moodley (2008).

3.2.1. Base case

Cooling water system in Figure 8 shows a set of heat exchanger networks which are supplied by a set of cooling towers. Each cooling water using operation is supplied by fresh water from the cooling tower and return back to the cooling tower. The implication of these arrangements results in higher return cooling water flow rate and low return cooling water temperature thus reducing cooling tower efficiency (Bernier, 1994).

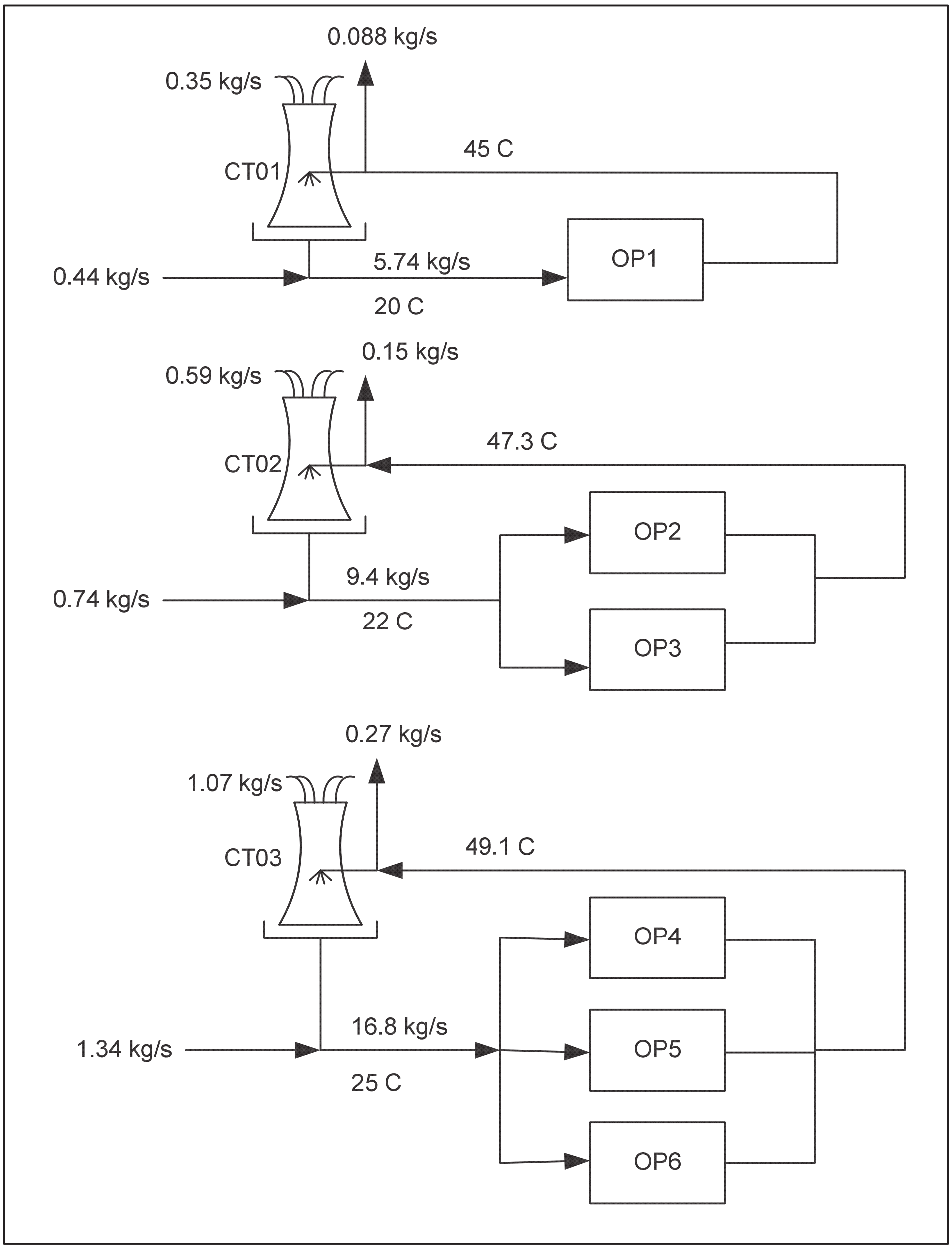

Figure 8. *Base case (Majozi and Moodley, 2008)*

The heat duties, temperature limits and design information are shown in Table 3 and Table 4. T^u_{ret} is the maximum allowable temperature for packing inside the cooling towers while OS^u is the maximum flowrate of the cooling tower before flooding. T^u_{in} and T^u_{out} are the thermodynamic temperature limits for the inlet and outlet temperature of the cooling water using operation respectively.

Table 3. *Cooling towers design information*

Cooling towers	$T_{ret}{}^{u}$ (C)	OS^{u}
CT01	50	9.6
CT02	50	16
CT03	55	20

Table 4. *Limiting cooling water data*

Operations	$T_{in}{}^{u}$ (C)	$T_{out}{}^{u}$ (C)	F_{in} (kg/s)	Q(i)(kW)
OP01	30	45	9.52	600
OP02	40	60	3.57	300
OP03	25	50	7.62	800
OP04	45	60	7.14	600
OP05	40	55	4.76	300
OP06	30	45	11.1	700

3.2.2. Case I

As aforementioned, 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 9 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.

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, as this is not entailed in the objective function.

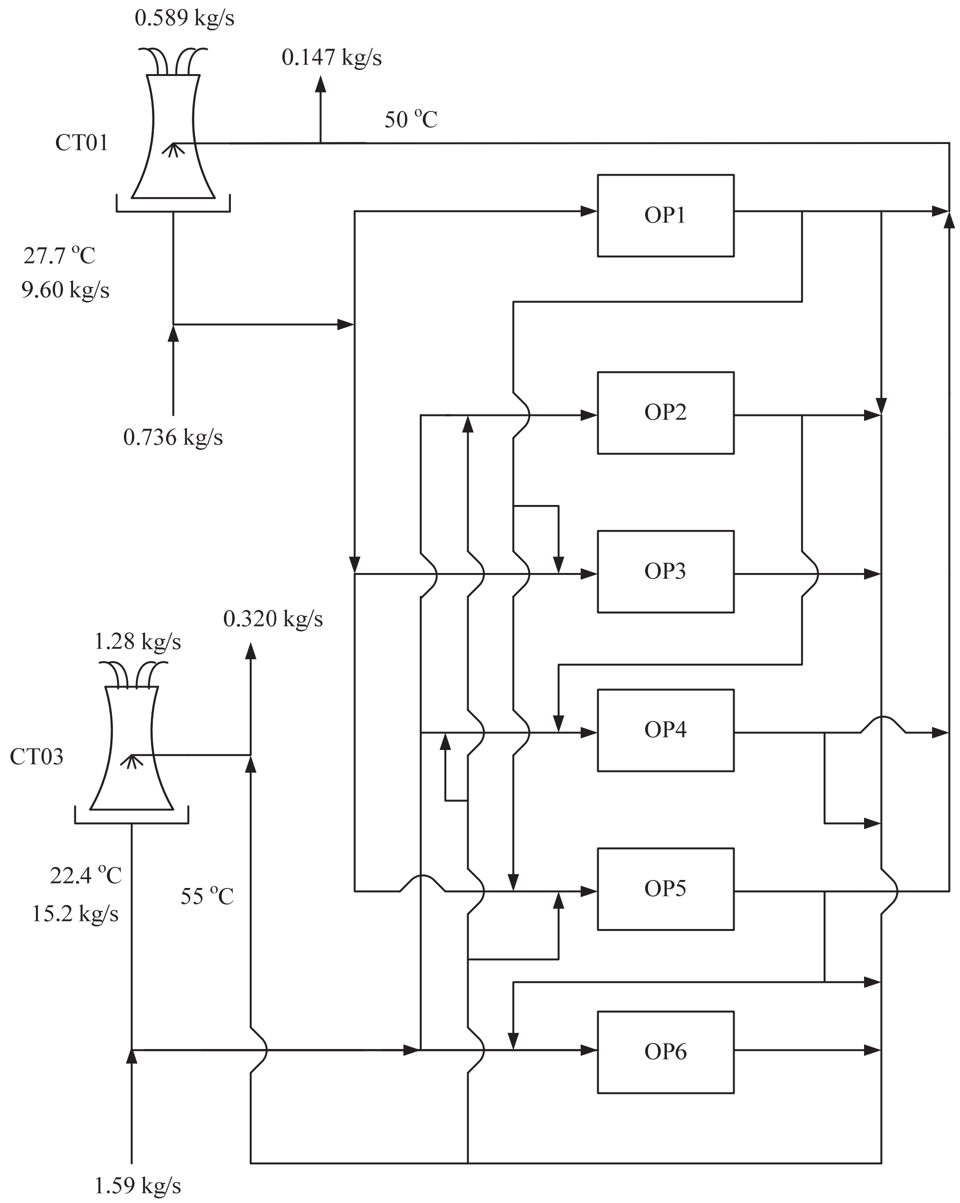

Figure 9. *Final design of the cooling water system*

Table 5. *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

3.2.3. 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 10 shows the heat exchanger network after applying the methodology described above.

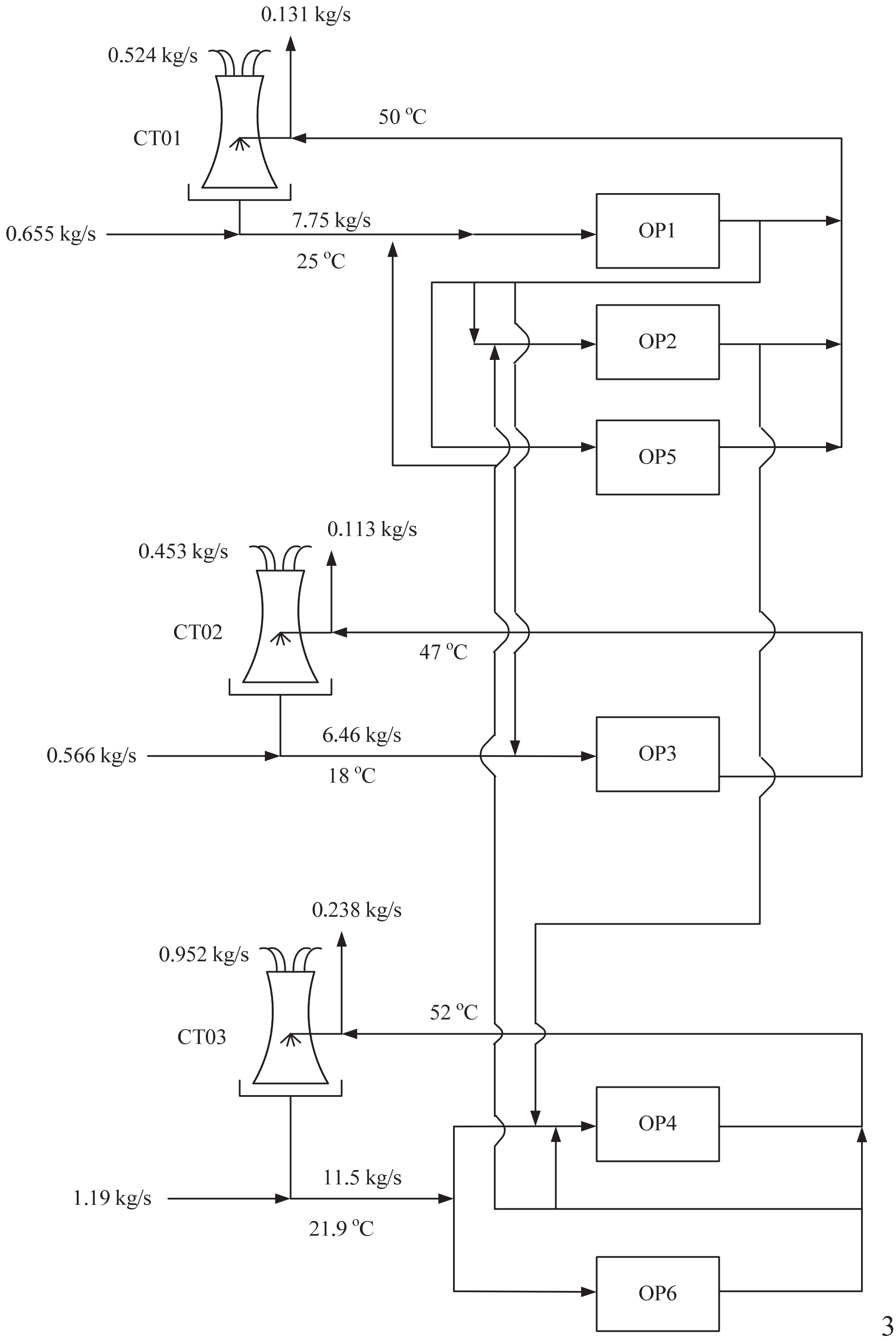

Figure 10. *Final design of the cooling water system*

By allowing for the cooling water reuse, the overall circulating water decreased by 20 %. 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 6. *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

3.3. Conclusions on Cooling Water System Design

The mathematical technique for cooling water system synthesis with multiple cooling towers has been developed. 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. There is also a potential for the reduction of makeup and blowdown water flowrate. The proposed technique shows a potential for capital saving in grassroots and retrofit designs.

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