Analysis of Optimal Control Strategies for Efficient Operation of a Produced Water Reinjection Facility for Mature Fields

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Abstract: Produced water management policies in oil and gas industry have been moving towards zero emission, no ocean discharge and waste-to-value conversion. Produced water reinjection plays a key role in achieving these goals for mature fields as it derives value from produced water and is able to maintain environmental integrity. A central element in this, is optimal operation of pumping. Hydraulic efficiency and specific energy are generally the chosen indices used to evaluate operational energy efficiency in pumping systems. In this work, we investigate optimization strategies based on natural objective function candidates for a produced water reinjection system: (i) operation at best efficiency point; (ii) minimization of total shaft input power; (iii) maximization of overall pump hydraulic efficiency; (iv) minimization of total specific energy and (v) minimization of total delivered energy. In addition, we discuss the implication of the different solutions over control structure selection.

Keywords: Scheduling and Optimization; Energy Processes; Industrial Applications; Optimal Control; Control Design

1. INTRODUCTION

1.1 Background

Mature fields are responsible for producing more than 70-80% of oil and gas worldwide (Ahmed, 2013). They can be defined as fields that are reaching their economic limit. This is because oil production is affected by the decline of the natural pressure difference (primary recovery) and by the decrease in oil recovery yield using water-flooding/gas injection of wells (secondary recovery) during initial phases (Babadagli, 2007). Due to natural water encroachment or employment of recovery techniques such as water-injection (Ahmed, 2004), mature fields have an increasing water-cut (water-to-hydrocarbon ratio) that can reach values above 97% (Afi et al., 2017). Thus, produced water represents the largest volume waste stream in oil and gas production both in onshore and offshore operations (Clark and Veil, 2009).

To handle the increasing amount of produced water, Veil (2011) suggests that decision making should be based on a three-tiered water management or pollution prevention framework. For each barrel of produced water there are costs related to pumping, storage, treatment and management. Therefore, the first tier is concerned with water minimization. Afterwards, in the second tier, economic value should be added to the produced water by recycling or reusing. Subsequently, in the third tier, the remaining water should be correctly disposed of by following environmental standards.

Produced water re-injection plays a major role (Abou-Sayed et al., 2007) in the second tier, as it extracts value from wastewater and mitigates environmental impact by reducing the discharge of produced water to the ocean. Specific attention should be given to zero-emission, discharge, and water-to-value conversion.

1.2 Literature review

Several articles have been exploring the usage of hydraulic efficiency to improve the operation of pumps. In general, centrifugal pumps are advised to be operated at their best efficiency point (BEP) (Gülich, 2014) as energy losses are reduced. If not, pumps become susceptible to harmful phenomena (Barringer, 2003) as operation continues and efficiency decreases. In Yang and Børsting (2010), an optimization problem is formulated to maximize total hydraulic efficiency of a group of identical parallel pumps. In Marchi et al. (2012), factors that affect hydraulic efficiency on a single variable-speed pump are explored.

Specific energy (Europump and Hydraulic Institute, 2005) is advocated in Steger and Pierce (2018) as a key performance criteria to reduce energy costs and extend the pump life cycle. Moreover, it is suggested in Ahonen (2011) that relative specific energy should be used to constrain the

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operation of the pump to guarantee a minimum energy efficiency. A comprehensive review of energy efficiency enhancement initiatives can be found in Arun Shankar et al. (2016).

At the same time, pumping optimization strategies have been primarily focusing on minimization of energy consumption costs (Mala-Jetmarova et al., 2017), with more recent works looking into pumping maintenance costs (Bene et al., 2013), operational reliability (Odan et al., 2015) and greenhouse gas emissions (Stokes et al., 2015). These additional objectives have been either incorporated in the optimization framework as constraints or as additional costs through a multi-objective approach.

Multi-objective approaches generally produce a set of Pareto solutions (Marler and Arora, 2004), which illustrates the trade-off between the different objectives. However, an additional step is necessary as one needs to choose a single solution out of a plethora of options. Due to that, multi-objective approaches may find resistance from operators as a clear decision for implementation is more desirable (Mala-Jetmarova et al., 2017).

In Olszewski (2016), single-objective approaches were investigated in a complex closed-loop pumping system composed of parallel pumps and auxiliary control valves. Minimization of power consumption and hydraulic efficiency has been considered, with the first being coined as the most reliable strategy. However, no further investigation is done with specific energy as an objective for the optimization problem.

In this work we investigate different single-objective optimization problems based on (i) operation at BEP; (ii) minimization of total shaft input power; (iii) maximization of overall pump hydraulic efficiency; (iv) minimization of total specific energy and (v) minimization of total delivered energy. A two-step strategy is used to analyze these strategies. First, we want to observe how control variables interact during the optimization of a system and second we want to see how these strategies perform when considering total shaft input power, total specific energy, total hydraulic efficiency and discharge ratio as performance indices. The waterflooding pumping station is based on an actual offshore production facility and its main characteristics are: serialized and parallel pumps; fixed-speed and variable-speed pumps; different characteristics of the pumps; open-loop pumping system; additional option to avoid pumping station; and presence of recycle valves.

2. PRODUCED WATER PUMPING STATION

2.1 System description

The studied pumping station is comprised of a degasser, two fixed-speed pumps, two variable-speed pumps, four recycle valves, two throttling valves and two disposal valves. In addition, pipelines perform the connection between these elements. Produced water enters the degasser from the produced water treatment facility and it is distributed between the produced water ocean disposal and the two parallel fixed-speed pumps. From there, produced water can be recycled to the degasser or continue towards the two parallel variable-speed pumps. After passing through the last pumps, it is possible to either recycle the produced water to the degasser or inject it to the injection wells by passing through the throttling valves.

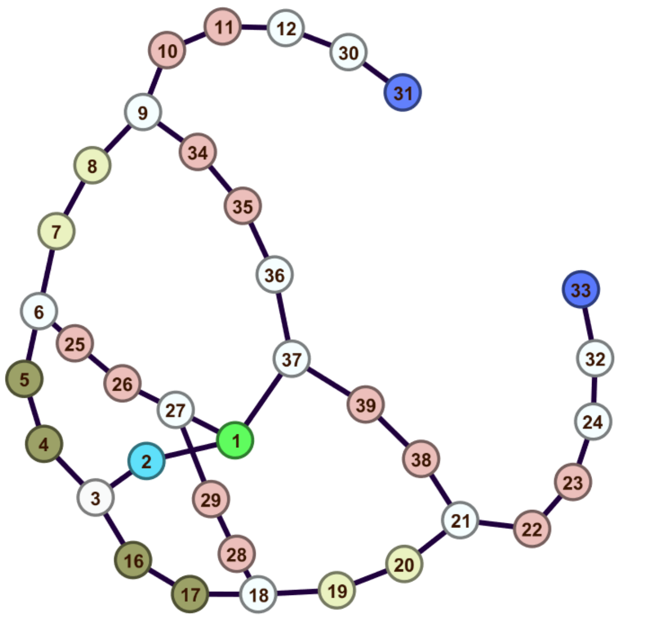

Fig. 1. Network representation of the produced water reinjection system. Legend: Tank (green); reservoir (dark blue); drain (light blue); control valve inlet and outlet (light red); fixed-speed pump inlet and outlet (brown); and variable-speed pump inlet and outlet (light yellow).

2.2 Network analysis definitions

Using nodal analysis, one can model the hydraulic network shown in Figure 1 by considering a set of nodes $J := \{n \mid n \in \{1, 2, ..., N\}\}$ and a set of arcs $L := \{(i, j) \in J \times J \mid i \neq j\}$. We further define junctions as $J_J \subset J$, tanks as $J_T \subset J$, reservoirs as $J_R \subset J$ and drains as $J_D \subset J$. In addition, we define pipelines as $L_P \subset L$, fixed-speed pumps as $L_{FS} \subset L$, variable-speed pumps as $L_{VS} \subset L$ and control valves as $L_V \subset L$.

We introduce the network structure in Figure 1. It is comprised of 37 nodes, of which there are 33 junctions, one tank, one drain and two reservoirs. Also, it has 39 arcs where; pump$_{(4/5)}$ and pump$_{(16/17)}$ are the two fixed-speed pumps; pump$_{(7/8)}$ and pump$_{(19/20)}$ are the two rotational-speed pumps; valve$_{(10/11)}$ and valve$_{(22/23)}$ are topside injection valves; valve$_{(25/26)}$ and valve$_{(28/29)}$ are recycle valves from fixed-speed pumps; valve$_{(34/35)}$ and valve$_{(38/39)}$ are recycle valves from the variable-speed pumps.

2.3 Nodes - Definitions

A common element to all nodes J are the hydraulic head $H := \{h_i \in \mathbb{R}^+ \mid i \in J\}$, pressure $P := \{p_i \in \mathbb{R}^+ \mid i \in J\}$, demand $D := \{d_i \in \mathbb{R} \mid i \in J\}$ and elevation $Z := \{z_i \in \mathbb{R}^+ \mid i \in J\}$.

The hydraulic head is a function of the reference elevation of the system,

$$h_i = \frac{P_i}{\gamma} + (z_i - z_0), \quad \forall i \in J \tag{1}$$

where z_0 is the reference elevation which is considered to be given by the node with lowest elevation $[m]$; and γ is the specific weight $\left[N/m^3\right]$.

In addition, the continuity equation must be satisfied for each node,

$$\sum_{\substack{i \neq j \\ i \in J}} [q_{ij} - q_{ji}] = d_j, \quad \forall j \in J \tag{2}$$

where q_{ij} is the flowrate from node i to node j $\left[m^3/s\right]$; q_{ji} is the flowrate from node j to node i $\left[m^3/s\right]$.

For junctions, it is assumed that produced water is neither removed or added to them; for the tank, produced water is added to it from upstream thus its demand is negative and known; for both drain and reservoir, produced water is removed which implies a positive demand. In addition, there is a minimal and maximum demand towards each reservoir that represents reinjection targets. For a mathematical description, we refer to (3), (4), (5), and (6), respectively.

$$d_j = 0, \qquad \forall j \in L_J \tag{3}$$
$$d_j < 0, \qquad \forall j \in L_T \tag{4}$$
$$d_j > 0, \qquad \forall j \in L_D \tag{5}$$
$$d_j^{min} \leq d_j \leq d_j^{max}, \quad \forall j \in L_R \tag{6}$$

For the reservoirs we use an injectivity index (Zarrouk and McLean, 2019) that relates its demand flowrate with its pressure:

$$P_j = a_j + b_j d_j, \quad \forall j \in J_R \tag{7}$$

where a_j and b_j are parameters that fit the injectivity index line.

2.4 Arcs - Definitions

Common elements for the arcs are given by the flow rate $Q := \{q_l \in \mathbb{R} \mid l \in L\}$ and hydraulic loss $H^{loss} := \{h_l^{loss} \in \mathbb{R} \mid l \in L\}$.

Arcs are responsible for connecting node $i \in J$ to node $j \in J$. Thus, the energy balance in terms of hydraulic head for each arc is given by

$$h_i - h_j = h_l^{loss}, \quad \forall l \in L. \tag{8}$$

In a pipeline, head loss can be described in terms of the Hazen-William formula

$$h_l^{loss} = 10.67\gamma \frac{q_l^{1.852} \Delta s}{C^{1.852} D_l^{4.87}}, \quad \forall l \in L_P \tag{9}$$

where Δs is the length of the pipeline $[m]$; D_l is the diameter of pipeline l $[m]$; and C is the Hazen-William constant. This equation is widely used in water distribution systems as well as surface waterflooding networks (Zhou et al., 2019) due to its simplicity and convenience.

Centrifugal pumps operate by converting shaft input power into hydraulic power. Each pump has its own characteristics and both fixed and variable speed pumps have been modeled by a linear interpolation of its manufacturer's curves. Thus, for each pump the head gain (i.e. negative of head loss) is shown by (10), while the shaft input power is seen in (11).

$$h_l^{gain} = \alpha_l^T x_l, \quad \forall l \in L_{FS} \cup L_{VS} \tag{10}$$
$$SP_l = \beta_l^T x_l, \quad \forall l \in L_{FS} \cup L_{VS} \tag{11}$$

where h_l^{gain} is the delivered head by pump l; x_l is the input vector of pump l; α_l is the delivered head parameter vector of pump l; SP_l is the shaft input power of pump l; and β_l is the shaft input power parameter vector of pump l.

The input vector of pump l is shown in (12) for fixed speed pumps and in (13) for variable speed pumps.

$$x_l = \begin{bmatrix} 1 & q_l & q_l^2 & q_l^3 \end{bmatrix}^T \qquad \forall l \in L_{FS} \tag{12}$$
$$x_l = \begin{bmatrix} 1 & w_l & q_l & w_l q_l & w_l^2 & q_l^2 & w_l^3 & q_l^3 \end{bmatrix}^T \quad \forall l \in L_{VS} \tag{13}$$

It is also possible to obtain curves from the manufacturer that limit a pump operational range. For the set of static speed pumps these are treated as bounds on the flow. As for the set of variable speed pumps, rotational speed is bounded and the maximum and minimum flow is a function of its head,

$$q_l^m = \sqrt{a_l^m + b_l^m h_l^{gain}}, \quad \forall l, m \in L_{VS} \times \{min, max\} \tag{14}$$

where q_l^m is the limit flow through the set of variable speed pumps; and both a_l^m and b_l^m are parameters of the curve. For valves, the headloss is calculated by

$$q_l = 27.3 \phi_l K \sqrt{\frac{h_l g}{100000}}, \quad \forall l \in L_V \tag{15}$$

where ϕ_l is the opening of valve l; K is the valve constant and ρ is the density of the fluid.

3. OBJECTIVE FUNCTION

In this section, we will look at natural choices for objective functions which are lately going to be compared and discussed for optimizing pumping system performance. The strategies are namely: (i) operation at best efficiency point (BEP); (ii) minimization of total shaft input power; (iii) maximization of overall pump hydraulic efficiency; (iv) minimization of total specific energy and (v) minimization of total delivered energy.

3.1 Strategy 1 - Operation at best efficiency point

When a pump is designed, there is a particular point of operation called the best efficiency point (BEP), which can be defined as the point where the hydraulic efficiency of a pump is at its maximum (Gülich, 2014). According to (Barringer, 2003) it is also associated with the operational health of the equipment. Thus, (16) is employed to lead pump operation towards the BEP.

$$\Psi^{BEP} = \sum_{l \in L_{FS} \cup L_{VS}} \left[\left(h_l^{gain} - h_l^{BEP} \right)^2 + \left(q_l - q_l^{BEP} \right)^2 \right] \tag{16}$$

where Ψ^{BEP} is the objective function associated with the best efficiency point; h_l^{BEP} is the head gain of pump l at the best efficiency point; and q_l^{BEP} is the flow rate of pump l at the best efficiency point.

3.2 Strategy 2 - Total shaft input power

The total shaft input power represents indirectly the operational cost associated with the power consumption of the pump and it is given in (17). Thus, it is a desirable optimization objective and widely used by the literature (Mala-Jetmarova et al., 2017).

$$\Psi^{SP} = \sum_l SP_l, \quad \forall l \in L_{FS} \cup L_{VS} \tag{17}$$

where Ψ^{SP} is the objective function associated with total shaft input power consumption.

3.3 Strategy 3 - Overall pump hydraulic efficiency

The pump hydraulic efficiency is defined as the ratio between the pump hydraulic power and the shaft input power input as shown in (18). It encompasses the hydraulic losses due to friction and turbulent dissipation in all components between suction and discharge nozzle.

$$\eta_l = \gamma \frac{h_l q_l}{SP_l}, \quad \forall l \in L_{FS} \cup L_{VS} \tag{18}$$

where η_l is the hydraulic efficiency of pump l.

It is considered a good performance criteria as it includes all the hydraulic losses between the suction and discharge nozzles. These energy losses can be dissipated into heat, vibration and noise, which can be harmful for the pumps (Barringer, 2003). Thus, the overall pump hydraulic efficiency is given as

$$\Psi^{\eta} = \gamma \frac{\sum_l h_l q_l}{\sum_l SP_l}, \forall l \in L_{FS} \cup L_{VS} \tag{19}$$

where Ψ^{η} is the objective function associated with overall pump hydraulic efficiency.

3.4 Strategy 4 - Total specific energy

Specific energy (Europump and Hydraulic Institute, 2005) is deemed as an alternative to estimate the pumping system energy efficiency. It is defined as the ratio between the pump's shaft input power input and its internal flowrate as seen in (20) for a single pump and on (21) for a pumping system.

$$E_{s_l} = \frac{SP_l}{q_l} = \gamma \frac{h_l}{\eta_l}, \quad \forall l \in L_{FS} \cup L_{VS} \tag{20}$$

$$\Psi^{E_s} = \frac{\sum_l SP_l}{\sum_l q_l}, \quad \forall l \in L_{FS} \cup L_{VS} \tag{21}$$

where Ψ^{E_s} is the objective function associated with total specific energy.

3.5 Strategy 5 - Total delivered energy

The delivered power consumption is calculated by (22) and represents the ratio between the pumps' total shaft input power and the total injected produced water.

$$\Psi^{E_d} = \frac{\sum_l SP_l}{\sum_i d_i}, \quad \forall l, i \in L_P \times J_R \tag{22}$$

where Ψ^{E_d} is the objective function associated with total delivered energy. This objective has some similarities with (21) as it is also a ratio between total shaft input power and flowrates. However, it is expected that (22) will reward more the injection of produced water to the injection wells as flowrate through pumps was replaced by reservoir demands.

4. OPTIMIZATION PROBLEM FORMULATION

Given the hydraulic network, an optimization problem can be formulated. It consists of the minimization of an objective function given aforementioned equality and inequality constraints. This can be mathematically expressed as follows:

$$\min_u \quad \Psi \tag{23.1}$$
$$s.t. \quad f(u,x) = 0, \tag{23.2}$$
$$g(u,x) \leq 0, \tag{23.3}$$
$$(u,x) \in \mathbb{X} \times \mathbb{U} \tag{23.4}$$

where Ψ is one of the objective functions presented in (16; 17; 19; 22); $f(u,x)$ are the equality constraints shown in (1; 2; 3; 7; 8; 9;10; 11; 14; 15); $g(u,x)$ are the inequality constraints defined in (14); u are the control variables bounded by $\mathbb{U} \in \mathbb{R}^m$ and x are the state variables bounded by $\mathbb{X} \in \mathbb{R}^n$.

The decision variables considered for this problem are $w_{(7,8)}$, $w_{(19,20)}$, $\phi_{(10,11)}$, $\phi_{(22,23)}$, $\phi_{(25,26)}$, $\phi_{(28,29)}$, $\phi_{(34,35)}$ and $\phi_{(38,39)}$. Each strategy was evaluated for three different values of d_1, minimum, nominal and maximum. It was considered that d_1 can deviate by 20% of its nominal value. Thus, the considered inlet ratios are 80%, 100% and 120%.

Optimization was done in CasADi (Andersson et al., 2019), an open-source tool for nonlinear optimization. To solve the problem, IPOPT (Wächter and Biegler, 2006) is used as we want to take full advantage of CasADi's automatic differentiating algorithm.

5. OPTIMAL OPERATION OF PRODUCED WATER REINJECTION

Table 1. Evaluated objective functions at optimum for each strategy and scenario.

Strategy	Inlet ratio	Objective	Units
Ψ^{BEP}	0.8	4.52	10^4
	1.0	4.47	10^4
	1.2	4.46	10^4
Ψ^{SP}	0.8	5645.66	kW
	1.0	5645.66	kW
	1.2	5645.66	kW
Ψ^{eta}	0.8	82.05	%
	1.0	82.05	%
	1.2	82.05	%
Ψ^{E_s}	0.8	1.8185	kWh/m^3
	1.0	1.8194	kWh/m^3
	1.2	1.8206	kWh/m^3
Ψ^{E_d}	0.8	5.65	kWh/m^3
	1.0	5.17	kWh/m^3
	1.2	5.17	kWh/m^3

To analyse the different strategies, we take into account the inlet ratio, which is defined as a factor that modifies the nominal demand $d_{(1)}$ by multiplying it. As a two steps methodology is being done, we start by analysing individually how the system operates to achieve the objective of aforementioned strategies. Afterwards, we look into how each strategy performs over total shaft input power, total specific energy, total hydraulic efficiency and

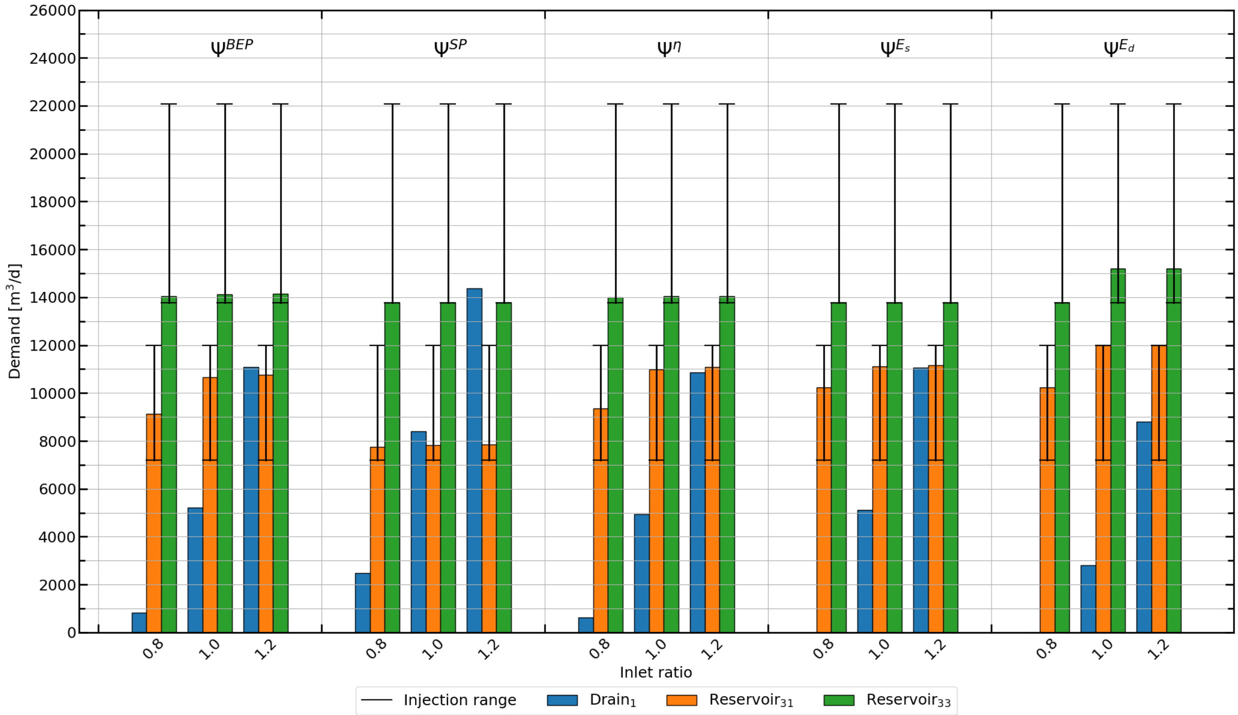

Fig. 2. Comparison of produced water demand for different strategies where changes in inlet ratio are considered.

discharge ratio, which is defined as the ratio between drain demand $d_{(2)}$ and tank demand $d_{(1)}$. Results for the optimal objective function of each strategy can be found in Table 1 and the decision variable results to operate the system are shown in Table 2.

The Ψ^{BEP} strategy tries to operate at pumps' best efficient point given by the manufacturer. No degrees of freedom are being consumed as there are neither active constraints or saturated control variables. Nevertheless, one degree of freedom has to be used for controlling the tank$_{(1)}$ water level. Thus, there are eight available degrees of freedom to guide the system towards its optimum. These are the same number of objectives as there is a desirable head gain and flowrate for each pump.

For the strategy Ψ^{SP}, the optimal objective function remains constant with changes in the inlet ratio as shown in Table 1, which means that the decision variables are able to counteract changes on the tank demand d_1. To perform that, produced water is routed towards the ocean as shown in Table 2 where there is only significant changes in the drain demand d_2. In addition, Figure 2 shows that the minimum reinjection constraint for reservoir$_{(33)}$ remains always active. When looking at valve opening ratio in Table 2, all recycle valves are closed, except for $\phi_{(34,35)}$, which is an indicator that recycle is needed for pump$_{(7,8)}$. Thus, it is necessary to check if the minimum constraint for $q_{(7,8)}$ is active, which is the case for all inlet ratio scenarios. By looking at the active constraints, only two degrees of freedom are available to control the system. However, level control is also required for tank$_{(1)}$. Thus, for steady-state optimal operation based on this strategy, one degree of freedom is left to use, which can be employed to regulate load sharing between drain$_{(2)}$ and reservoir$_{(31)}$.

On strategy Ψ^{η}, the optimal objective function also remains constant for all scenarios, which is an indicator that there are enough degrees of freedom to maintain the overall hydraulic efficiency at its optimum. For that, a minimum of four degrees of freedom are needed. From Table 2, one can see that just control actions $\phi_{(25,26)}$, $w_{(7,8)}$ and $w_{(19,20)}$ remains saturated, while all other control actions remains changing with $d_{(1)}$. Also, none of the flowrate constraints are active. As one needs to control the tank's level, five degrees of freedom are left, where four are used by the objective function and one remains available.

Strategy Ψ^{E_s} has its optimal objective function changing with $d_{(1)}$. From Table 2, there are two sets of six saturated decision variables, which differ depending on the inlet ratio scenario. In addition, minimum flowrate constraint of reservoir$_{(33)}$ and maximum flowrate constraint of pump$_{(4,5)}$ are active, giving a total of eight active constraints. As tank$_{(1)}$ level control is always needed, the solution of the optimization problem remains fully constrained.

The strategy Ψ^{E_d} changes its priorities based on inlet ratio. At the lowest inlet ratio, most of the recycles are kept closed, with the exception of $\phi_{(34,35)}$. Thus, investigation of active flowrate constraint is needed. For pump$_{(7,8)}$, minimum flowrate constraint remains active. The same is true for reservoir$_{(33)}$. For this scenario in particular, the optimization problem is fully constrained as all degree of freedom are being consumed to maintain the two minimum flowrate constrains active and six decision variables saturated. In addition, one degree of freedom is being used to control the tank$_{(1)}$ level. As for nominal and high scenarios, the set of active constraints changes. First, the maximum flowrate constraint for reservoir$_{(31)}$ is now active and no recycle is being used. Second, the flowrate

Table 2. Optimal values for decision variables used to operate the produced water reinjection system.

Strategy	Inlet ratio	$\phi_{(10,11)}$ [%]	$\phi_{(22,23)}$ [%]	$\phi_{(25,26)}$ [%]	$\phi_{(28,29)}$ [%]	$\phi_{(34,35)}$ [%]	$\phi_{(38,39)}$ [%]	$w_{(7,8)}$ $[rpm]$	$w_{(19,20)}$ $[rpm]$	$d_{(2)}$ $\left[m^3/h\right]$
Ψ^{BEP}	0.8	12.18	21.96	4.18	6.31	74.93	14.63	4515	4135	34.66
	1.0	15.83	22.21	4.14	6.26	65.29	14.07	4515	4135	217.66
	1.2	16.17	22.26	4.14	6.26	64.54	14.00	4515	4135	462.13
Ψ^{SP}	0.8	12.44	39.40	0.00	0.00	22.93	0.00	3739	3440	103.02
	1.0	12.64	39.46	0.00	0.00	22.43	0.00	3739	3440	350.02
	1.2	12.70	39.54	0.00	0.00	22.32	0.00	3739	3440	599.34
Ψ^{η}	0.8	11.23	72.76	0.00	55.87	89.61	24.32	4907	3440	26.35
	1.0	14.45	76.14	0.00	55.98	79.78	23.85	4907	3440	206.24
	1.2	14.65	76.83	0.00	56.15	79.28	23.87	4907	3440	452.68
Ψ^{E_s}	0.8	23.91	100.00	100.00	100.00	5.98	34.38	3739	3440	0.00
	1.0	32.20	100.00	100.00	100.00	0.00	34.20	3739	3440	213.37
	1.2	33.20	100.00	100.00	100.00	0.00	33.97	3739	3440	460.75
Ψ^{E_d}	0.8	22.00	39.38	0.00	0.00	5.39	0.00	3739	3440	0.00
	1.0	43.21	100.00	0.00	0.00	0.00	0.00	3739	3440	116.69
	1.2	43.32	100.00	0.00	0.00	0.00	0.00	3739	3440	366.93

Table 3. Ranking and mean value of each strategy based on performance indices.

Ranking	Total shaft input power		Total specific energy		Total hydraulic efficiency		Discharge ratio	
	Strategy	Value [kW]	Strategy	Value [kWh/m^3]	Strategy	Value [%]	Strategy	Value [%]
1st	Ψ^{SP}	5645.66	Ψ^{E_s}	1.820	Ψ^{η}	82.04	Ψ^{E_d}	11.27
2nd	Ψ^{E_d}	5785.94	Ψ^{E_d}	2.635	Ψ^{BEP}	78.06	Ψ^{E_s}	15.92
3rd	Ψ^{E_s}	6371.77	Ψ^{SP}	2.736	Ψ^{E_s}	74.20	Ψ^{η}	16.44
4th	Ψ^{BEP}	10231.94	Ψ^{η}	2.847	Ψ^{E_d}	72.58	Ψ^{BEP}	17.23
5th	Ψ^{η}	10431.29	Ψ^{BEP}	3.258	Ψ^{SP}	70.86	Ψ^{SP}	26.09

constraints of the pumps are inactive. Thus, if there is enough produced water entering the system, this strategy leads to a no-recycle policy.

We continue to evaluate the different strategies by following through Table 5, which lists the ranking of each strategy for a particular index. As one can see, strategy Ψ^{SP} was the best strategy when considering only total shaft input power. Nevertheless, it is closely followed by strategy Ψ^{E_d} as its power usage is 2.48% higher than strategy Ψ^{SP}.

Strategy Ψ^{E_s} has reached the highest rank for total specific energy by a margin of 44% when compared with Ψ^{E_d}. However, this performance is considered misleading. During the first part of this methodology, it was reported that strategy Ψ^{E_s} operates with several recycle valves open and that maximum flowrate constraints of pump$_{4,5}$ are constantly active. This shows that, despite reaching a low total specific energy, this strategy wastes part of it through recycling.

For the total hydraulic efficiency, strategy Ψ^{ρ} has attained the highest ranking for efficiency and performing even better than Ψ^{BEP}. According to Barringer (2003), it is considered best practice of the pumps to operate with hydraulic efficiency above 92% of the best efficiency point strategy. For this particular case, only strategy Ψ^{SP} operates below this threshold.

When considering the discharge ratio to the ocean, strategy Ψ^{E_d} has the best score as it was able to reduce the discharge ratio levels to 11.27%. This is 61.06% lower than the second best strategy, *i.e.* Ψ^{E_s}, and 70.73% lower than strategy Ψ^{SP}, which has the worst performance over this criteria.

6. CONCLUSION

In this work we have evaluated the performance of several objective functions by executing a behavioral analysis over the following strategies: (i) operation at best efficiency point (BEP); (ii) minimization of total shaft input power; (iii) maximization of overall pump hydraulic efficiency; (iv) minimization of total specific energy and (v) minimization of total delivered energy. This methodology was done with a two-step analysis involving: first, decision variables and inequality constraints; and second, different indices for strategy performance evaluation. From this analysis, it is clear that the commonly used strategy Ψ^{SP} prioritizes produced water discharge towards the ocean as a way to reduce total input shaft power consumption. Thus, we see this strategy as non-environmental friendly. In addition, risks associated with the life cycle of the pumps may contribute to increased operational cost. Strategy Ψ^{η} prioritizes maximization of system hydraulic efficiency and for this study increased greatly the consumption of power through shaft input power, which is not desirable. We recommend the usage of strategy Ψ^{E_d}, known as minimization of total delivered energy, as it performs economically similar to Ψ^{SP}, leads to a decrease in recycling by having an implicit non-recycle policy and is able to decrease produced water discharge to the ocean.

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