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Cost-effective sustainable operation policy of Jeddah RO desalination plant under production pumps failure using mathematical programming

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ABSTRACT

Seawater desalination is one of the most important means of securing water for domestic needs in arid geographical regions such as Saudi Arabia. Water production of Jeddah desalination plant is critical in meeting the city's increasing water demands. The plant uses reverse osmosis technique with a production system consisting mainly of a permeate tank and production pumps. Failure or shutdown of any operating pump causes serious issues in demand and loss of production. The objective of this study is to develop a cost-effective operation policy that ensures the plant's continuous production rate throughout the failure of any production pump. Mathematical optimization technique is used to explore possible and optimal solutions for the plant's operation policies. The case was formulated as mixed-integer programming to minimize an objective function. POM-QM for Windows package was used to solve the problem using branch and bound method. This mathematical programming proved to be a powerful technique not only in solving for an optimal solution of a minimization problem, but also in generating a nearly optimal feasible solution of best operation policy in a given setting of water production system. The technique is capable of solving the optimal operation policy at minimal cost for any given scenario in the solution space under the shutdown condition of any operating pump. In addition to saving operational and maintenance costs, the obtained solutions can be adopted to prevent huge quantities of water production from being wasted into the sea. Hence, these solutions exhibit best practice and management of water resources.

Keywords: Seawater desalination; Mixed-integer programming; Pump failure; Cost-effective; Optimal solution; Jeddah

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1. Introduction

Water is scarce in Saudi Arabia. Due to geographic location, climatic conditions, limited groundwater resources, and need for reliable water supplies near population centers, seawater desalination is one of the most important methods of securing water for domestic needs. Desalination in Saudi Arabia started in 1928. In 1974, the Saline Water Conversion Corporation (SWCC) was established to carry out the necessary feasibility and preliminary studies for installing desalination plants in the Red Sea and the Arabian Gulf and for maintaining the currently operating desalination plants [1]. The seawater reverse osmosis (SWRO) desalination plant, Jeddah reverse osmosis (RO) Phase 1, commissioned in 1989, has a capacity of 48,848 m/d. In 1994, desalination plant Jeddah RO Phase 2 was commissioned with a capacity of 50,000 m/d. The desalinated water is poured into the product tank which functions as a sump to a pumping system that supplies Jeddah city. RO plants in Jeddah use hollow fine fiber membranes with a highly soluble Aramid polymer (Aromatic Polyamide) acting as durable thick-walled pipes under pressure. These homogeneous membranes have the largest intrinsic life of any RO membrane, as demonstrated by their very low replacement rate and very low cost-in-service [2]. These membranes also ensure constant high salt rejection even under the most demanding high salinity and high temperature conditions prevalent in the region. Recently, in response to the need for more water supplies due to increasing population and higher living standards, SWCC decided to refurbish and upgrade the complete operational control and automation system. This process resulted in increasing the desalinated water discharge such that the present pumping system works with all pumps including standby pumps. Therefore, if any pump fails or needs regular maintenance, the product tank overflows and desalinated water is wasted in the sea.

After an optimal design of the drinking water network of water production systems, further economic efficiency can be reached through optimal management of operational activities such as production scheduling and pump switching [3]. The authors found that most drinking water companies neglect these savings by operating their networks based upon experience. In this regard, an operational support model that minimizes production costs over a finite horizon is extremely useful. Production in drinking water networks can be modeled as a minimum flow problem with many side constraints, such as an optimization approach. This model is expanded with more complicated constraints resulting from the network hydraulics. Verleye and Aghezzaf [3] explored an operational planning model aiming at minimizing production and distribution costs in large drinking water networks containing buffers with free inflow.

Energy required for operating pumping stations in the distribution of water may be significant. The extensive cost of establishing new pumping stations and the increasing cost of energy have caused researchers to pay more attention to the optimal design and operation of pumping stations [4–6]. Attempts to improve the design and operation efficiency of existing or newly developed pumping stations are continuously increasing. Extensive-scale direct SWRO plants should run at high standards as a result of the increasing cost in water production with high quality, high equipment application, treatment, along with more government regulations in the area of environment protection [7–9]. Optimization approach is most suitable in cases where problems (1) are clearly defined with quantified objectives; (2) can be expressed by mathematical model; and (3) have enough data to distinguish between alternative solutions [10]. Energy cost optimization of a water supply network is an essential practical problem. For instance, the savings that would accrue from only a 5% reduction in the total power consumed in the US has been estimated at $48,000,000 per year [11].

Avlonitis [12] developed a mathematical model and software for the optimum design of SWRO plant with an objective to minimize energy cost. The results of the developed model were tested experimentally and verified by RO system analysis software, with the conclusion that the developed model was both reliable and simple. Yechiel and Shevam [13] utilized linear programming to optimize the operation of RO plant in order to reduce energy costs. They reported a 15% reduction in the plant's electricity bill, thereby showing that linear programming could be used as an efficient tool for decision-making. The objective of this study is to manage the production of Jeddah's RO desalination plant through mathematical programming that ensures a cost-effective sustainable daily flow of desalinated water.

2. Methodology

2.1. Jeddah RO plant

Jeddah's desalination plant is located in Jeddah city on the shore of the Red Sea. The plant consists of four stations. There are two reverse osmosis (RO-1 and RO-2) stations with a total capacity of approximately 98,000 m^3/d, and two multi-stage flash distillation stations with a total capacity of approximately

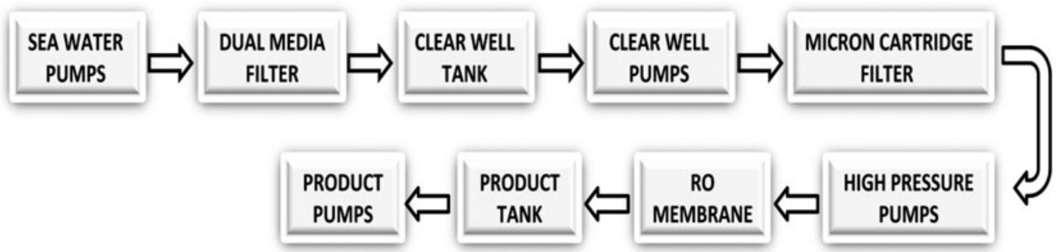

Fig. 1. Schematic diagram of Jeddah RO plant.

267,000 m^3/d. The plant is fed seawater from open sea intake with TDS of up to 36,000 ppm. Each RO station contains 10 RO units. Fig. 1 illustrates a schematic representation of Jeddah RO process.

The RO process consists of several steps. The first step, intake, consists of sea water intake, traveling screen, and sea water pump. The second step is pretreatment, where sea water is introduced to a dual media filter to remove suspended solids, then stored in a clear water tank. The clear water is then pumped to a micron cartridge filter to remove fine suspended matters and prevent any salt precipitation or microbial growth on membranes. The third step (RO system) pumps the pretreated water at high pressure (average of 900 psi) through the membranes to remove the salt where the brine water is drained to the sea and the desalinated water is introduced to the fourth step. Desalinated water is stored in the product tank and is then pumped to the city. The product pump consists of three pumps: two main pumps and one standby. Table 1 displays Jeddah plant components characteristics.

The RO station originally produces 2,360 m^3/h which is poured into a balance tank. This flow represents 35% of the sea water drawn from the Red Sea. The tank works as a sump for the pumping station, where the water is pumped through a pipe line to Jeddah city (Fig. 2). The pipe line is equipped with a level control valve to control the water level in the tank so that the input flow to the tank equals the outflow. Recently, with the upgrade of the RO operation system (including increasing the applied pressure on the membranes), the desalinated water increased to 2,700 m^3/h; a recovery of 40%. To deal with the new condition, the standby pump operates as a main pump. As such, if any pump fails or needs maintenance, the tank overflows and the desalinated water is wasted in the sea.

Table 1
Jeddah plant components characteristics

Steps	Components	Characteristics
Intake	Sea water intake	Two 1,400 mm pipeline, capacity 14,682 m^3/h
	Traveling screen	Capacity 4,894 m^3/h
	Sea water pump	Capacity 4,374 m^3/h
Pretreatment	Dual media filter	Gravity (anthracite, fine sand, and gravel) size: 4.2 m W, 16 m L and 4.2 m H
	Clear water tank	Rectangular, size: 22 m W, 21.9 m L and 9.4 m H, effective capacity 1,600 m^3
	Clear water pump	Two mixed flow vertical pumps, capacity 3,500 m^3/h each
	Micron cartridge filter	10 cylindrical units, capacity 3,500 m^3/h
RO system	High pressure pumps	10 pumps, capacity 700 m^3/h each
	RO units	10 units, capacity 700 m^3/h each, product 270 m^3/h, recovery 40%, maximum pressure 1,000 psi
	Back flow tank	Rectangular, size: 11.5 m W, 8 m L and 8.75 m H, effective capacity 300 m^3
Output	Product tank	Rectangular, size: 11.5 m W, 7.95 m L and 8.75 m H, effective capacity 700 m^3
	Product pump	Three double suction volute pump, horizontal, capacity 1,200 m^3/h each, pressure 40 m

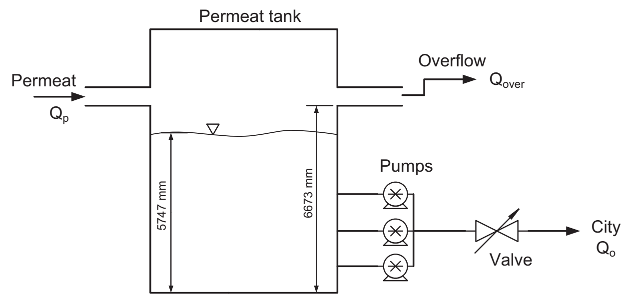

Fig. 2. Storage-delivery system components of Jeddah desalination plant.

2.2. Mathematical formulation

Mixed-integer programming is envisioned in the exploring of a solution for the present problem, as it has proven effective in dealing with many similar problems [14,15]. The problem can be stated as follows: an input with specific discharge is poured into a balance tank that works as a sump to a pumping system consisting of a number of pumps including standby, as shown in Fig. 2.

The objective is to develop a cost-effective operation policy that ensures Jeddah plant's continuous production rate during the failure of any production pump. The problem may be formulated as a minimization optimization model as follows:

Objective function:

$$\text{Min } Z = \sum_{i=1}^{N} C_i P_i + C_j T_j + M_i P_i \tag{1}$$

Subject to:

(1) Water demand constraint

$$\sum_{i=1}^{N} Q_i P_i \geq Q_t \tag{2}$$

(2) Production budget constraint

$$Q_{\text{in}} - Q_{\text{out}} \leq V_j T_j \tag{3}$$

(3) Logical constraint

$$T_j \geq 1 \tag{4}$$

(4) Nonnegative constraints

$$P_i, T_i \geq 0 \tag{5}$$

where C_i = unit capital cost of pump i; P_i = No. of pump i; T_j = No. of tank j; M_i = unit cost of power consumption plus maintenance cost; C_j = unit cost of tank j; Q_t = target flow per unit time; Q_{in} = inlet flow per unit time; Q_{out} = outlet flow per unit time; Q_i = pump production rate; and V_j = volume of the tank.

The solution of the problem as described above would lead to a number of pumps with a specific capacity, a number of production tanks, and a value of the objective function. To obtain a meaningful solution, it is therefore essential to select pumps that exist in the local market. A list of available pumps is used to formulate the model equations. The associated maintenance and energy costs are based on analysis of records from Jeddah's desalination plant.

2.3. Solution technique

The most widely used method for solving integer programs is branch and bound. Subproblems are created by restricting the range of the integer variables. Variable with lower bound L and upper bound U will be divided into two problems with ranges L to X and $X+1$ to U, respectively. Lower bounds are provided by the linear programming relaxation to the problem; keep the objective function and all constraints, but relax the integrality restrictions to derive a linear program. If the optimal solution to a relaxed problem is (coincidentally) integer, it is an optimal solution to the subproblem, and the value can be used to terminate searches of subproblems whose lower bound is higher. We focused specifically on LP-based branch and bound, in which LP relaxations of the original problem are solved to obtain bounds on the objective function value of an optimal solution. The original problem is then reduced to a series of smaller subproblems, and then recursively solves each subproblem. For more details, the reader is referred to the technical report by Jens Clausen [16].

Both commercial and noncommercial packages to solve mixed-integer linear programming (MILP) are available. For an excellent overview of the major algorithmic components of commercial solvers, the reader is referred to the paper of Atamturk and Savelsbergh [17]. POM-QM, ABACUS, BCP, BonsaiG, and CBC are a few examples of noncommercial solvers of MILP. We have used POM-QM [18] for Windows to solve the optimization problem of Jeddah's desalination plant.

2.4. Objective function parameters

The coefficients of the objective function parameters are mainly capital cost of pump, cost of maintenance

Table 2
Capital and total cost of pumps (P_i) and product tank (T_i) available in the local market

Notation variable of pump (P_i)	Discharge capacity (m^3/h)	Capital cost (SAR)	Total cost (SAR)
P_1	2,500	525,000	2,188,000
P_2	2,000	475,000	1,804,000
P_3	1,500	435,000	1,431,000
P_4	1,200	375,000	1,171,000
P_5	1,000	325,000	989,000
P_6	600	225,000	624,000
P_7	360	100,000	333,500
P_8	260	70,000	237,000
P_9	200	50,000	183,500
T_1	1,000 (m^3)	340,000	

Note: Total cost include capital cost plus power consumption and maintenance.

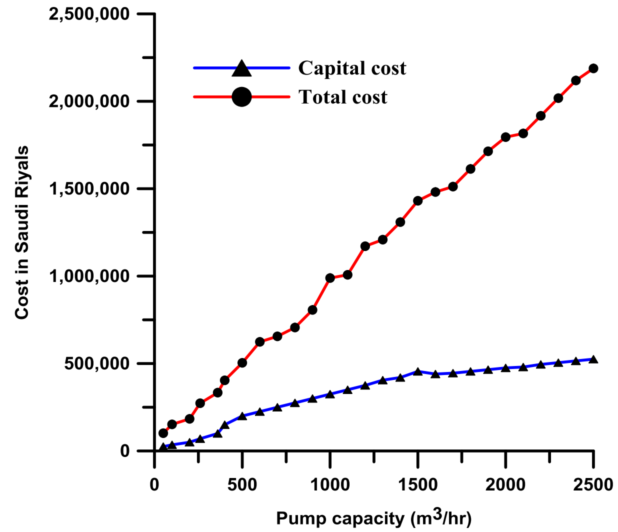

Fig. 3. Plots of pump capacity vs. capital and maintenance costs.

and power, and cost of product tank. Table 2 shows costs and capacities of pumps and tank collected from the local market. There were nine different pump capacities and one size of product tank. The product tank can be manufactured to a size of choice; however, the space available in Jeddah's plant fits a tank of 1,000 m^3. The total cost of a single pump indicated in Table 2 refers to the sum of capital cost, maintenance cost, and power cost. It is certain that capital and total costs of pumps increase with the increase in capacity specification; however, the rate of increase is not constant but is instead close to linear.

Plots of pump capacity vs. costs are shown in Fig. 3. The trend follows an almost linear trend with slight fluctuation and changing slopes, especially in the case of capital cost. Both relationships have an effect on the results of the optimization problem, as shown below.

3. Results and discussion

3.1. Pump failure cases

Two scenarios of pump failure were considered feasible solutions in the optimization problem of Jeddah's production plant. The first scenario is the failure of pump P_1 ($Q = 2{,}500$ m^3/h) and the second scenario is the failure of pump P_4 ($Q = 1{,}200$ m^3/h). While other pump capacities can also be tried, these two pumps represent the current conditions in Jeddah's plant. Both integer and noninteger (real) constraints on the decision variables were considered. Table 3 displays a summary of solutions for the optimization problem obtained under the two scenarios, both with and without the inclusion of power and maintenance costs. Because the number of feasible solutions was many, values of the objective function, number of pumps, and pump production rate are presented in terms of ranges. For example, in the case of pump P_1 failing when only capital cost is considered, 16 feasible solutions were obtained. The number of pumps was 2–14, the cost was in the range of $1{,}440 \times 10^3$–$1{,}915 \times 10^3$ Saudi Riyals (SAR), and the production rate range was 2,700–5,000 m^3/h. Solution parameters under the failure of pump P_4 were similar to those of pump P_1 in terms of number of feasible solutions, number of pumps, and production rate, but differed in the value of the objective function. Number of feasible solutions depends on the solution type (integer and noninteger). These solutions are always greater in the case of noninteger regardless of the inclusion or exclusion of power and maintenance costs. This result is expected because the solution space of real numbers that fulfill the proposed constraints is much greater than the constraint space of integer numbers.

On the other hand, solutions for the failure of pump P_4 always produce less values of objective function compared to solutions for the failure of pump P_1 because the failure of pump P_4 allows the minimization process to choose another pump P_4 which is cheaper than the pump P_1, thus reducing the cost (value of the objective function). Likewise, costs of power and maintenance are found to be more than three times that of the capital cost. The breakdown of power and maintenance costs or the development of cost function was not explored in this study, a matter that may contribute to cost reduction or further minimization of objective function.

Table 3
Solution summary of the optimization problem under pump failure with and without power and maintenance costs consideration

Pump failure	Solution type	No. of feasible solutions	No. of pumps	O.F. value × 10^3 (SAR)	Production rate (m^3/h)
Power and maintenance costs excluded					
P_1	I	16	2–14	1,440–1,915	2,700–5,000
	NI	37	2.04–8.22	1,411–1,839.25	2,520–2,610
P_4	I	16	2–14	1,290–1,765	2,700–5,000
	NI	37	2.04–8.22	1,261–1,689.25	2,520–2,610
Power and maintenance costs included					
P_1	I	47	2–14	4,882.5–6,904	2,400–5,000
	NI	83	2.04–8.22	4,803.52–5,787.5	2,280–2,600.5
P_4	I	47	2–14	3,865.5–5,887	2,400–5,000
	NI	83	2.04–8.22	3,786.52–4,770.5	2,280–2,600.5

Note: I: Integer; NI: Noninteger.

3.2. Solution spaces

Figs. 4 and 5 show the solution space of the production rate vs. the objective function due to the failure of pump P_1 with and without the inclusion of power and maintenance costs. Note that the mixed-integer solution space (gray circles) is much narrower than the integer solutions (blue circles); each blue circle designates a feasible solution. The narrow range indicates the sensitivity of the mixed-integer solution to the production rate. The two figures also show the optimal solution (red color). The posted inequalities on the integer solutions of Fig. 4 indicate the added constraints to the optimization problem as a result of implementing branch and bound method. Due to redundancy, inequalities have not been shown in the consequent figures. Similarly, Figs. 6 and 7 show the solution space due to the failure of pump P_4. Trends in the solution space and solution types of the failure of pump P_1 and pump P_4 are almost the same. However, the cost due to the failure of pump P_4 is always less than the cost when pump P_1 fails. This result indicates preference for selecting a solution that adopts the failure of pump P_4; nevertheless, details of the resultant optimal solution in the next section further clarify this result.

3.3. Optimal solutions

POM-QM solves all feasible, nonfeasible, integer, and noninteger solutions. Table 4 shows only the

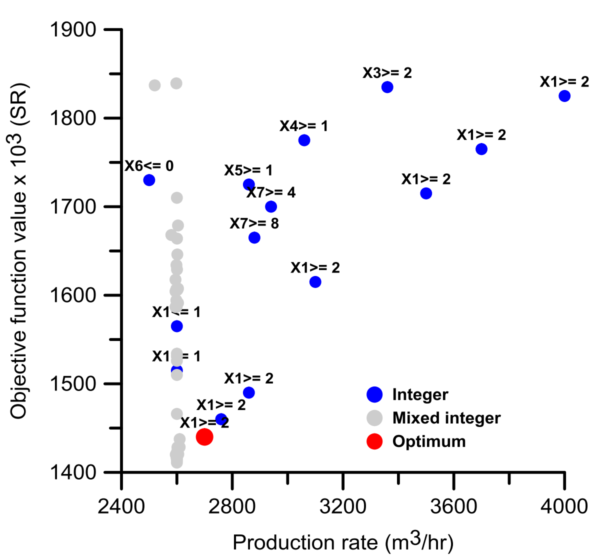

Fig. 4. Solution space under the failure of pump P_1 with the consideration of power and maintenance costs.

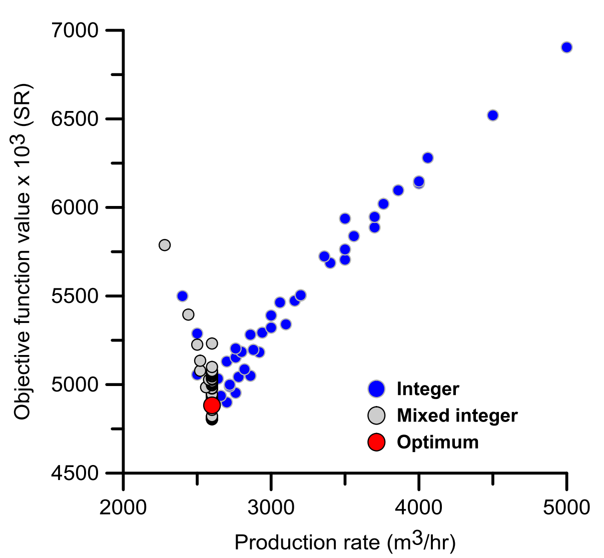

Fig. 5. Solution space under the failure of pump P_1 without the consideration of power and maintenance costs.

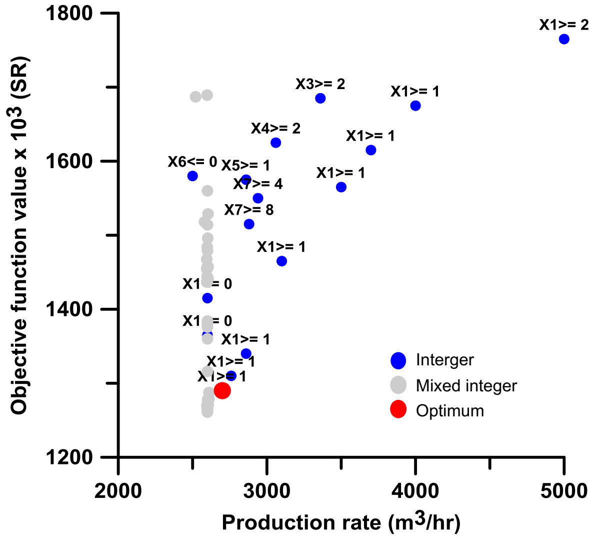

Fig. 6. Solution space under the failure of pump P_1 with the consideration of power and maintenance costs.

optimal solutions under pump failure conditions with and without consideration of power and maintenance costs. In the case of the failure of pump P_1 when power and maintenance costs are not included, the best choice of operation is to use only two pumps of type P_1 and one pump of type P_9. This will cost 1.44 million SAR. However, in the case of the failure of pump P_4, the best choice of operation is to use a total of three pumps of type P_1, P_4, and P_9. This will cost 1.29 million SAR which is less than the cost of pump P_1 failure. On the other hand, when power and maintenance costs are included, the solution completely changes. In this case,

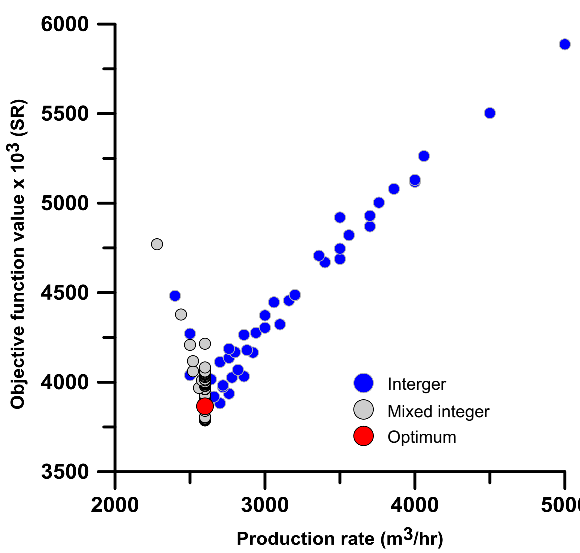

Fig. 7. Solution space under the failure of pump P_1 without the consideration of power and maintenance costs.

the optimal solution under the failure of pump P_1 was found to be as follows: use one pump of type P_1, one pump of type P_2, and three pumps of type P_9, altogether costing 4.88 million SAR. When pump P_4 fails, the suggested solution is to use one pump of type P_2, one of type P_4, and three pumps of type P_9. This costs 3.86 million SAR which is less than the cost of the failure of pump P_1.

Besides the integer optimal solutions, Table 4 also presents the results of noninteger optimal solutions. The noninteger solution produced 12% lower costs than that obtained by the integer solution. This percentage doubles when power and maintenance costs are included. The noninteger number of pumps under this type of solution seems unrealistic; instead, an integer number is mandatory. However, the number of pumps, for example 2.04 or 1.04 in Table 3, can be viewed as an indication of production from which pumps with desired specifications can be manufactured. Theoretically speaking, 2.04 pumps of type P_1 with a production rate of 2,500 m^3/h is equivalent to two pumps of type P_1, where each P_1 is specified to have a production rate of 2,550 m^3/h. Although such pump specifications are not available in the local market, these could be manufactured with customized specifications. Adapting this option certainly reduces the total cost over the long run even after considering costs of the new pump, power, and maintenance.

3.4. Near optimal solution adoption

The nearly optimal noninteger feasible solutions are many, as shown in Figs. 4–7, and depicted as circles near the optimal solution. There are 12 such solutions under the failure of pump P_1 when only capital costs are considered, while the number of solutions increases to 22 when power and maintenance costs are included. Similar results were obtained under the failure of pump P_4. Any of these feasible solutions can be adopted, as they cost less than the optimal solution, bearing in mind that pump manufacturing customization is required. More important is the number of pumps that the optimization model produced. There were no constraints set in the optimization model on the number of pumps or space. However, there are three to four pump spaces available in the case of Jeddah's plant. Accordingly, selection of any feasible solution must meet this external constraint. A closer look into the detailed results of the optimization problem (not presented) under capital costs consideration indicated that all nearly optimal solutions advise the use of less than four pumps, regardless of the failure of any specified pump type. On the other hand, when

Table 4
Optimal solutions under pump failure conditions with and without power and maintenance costs consideration

Pump failure	Solution type	No. of pumps of type (P_i)									Production rate (m^3/h)	Value of O.F. × 10^3 (SAR)
		P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9		
Power and maintenance costs excluded												
P_1	I	2	0	0	0	0	0	0	0	1	2,700	1,440
	NI	2.04	0	0	0	0	0	0	0	0	2,600	1,411
P_4	I	1	0	0	1	0	0	0	0	1	2,700	1,290
	NI	1.04	0	0	1	0	0	0	0	0	2,600	1,261
Power and maintenance costs included												
P_1	I	1	1	0	0	0	0	0	0	3	2,600	4,882.5
	NI	2.04	0	0	0	0	0	0	0	0	2,600	4,803.52
P_4	I	0	1	0	1	0	0	0	0	3	2,600	3,865.5
	NI	1.04	0	0	1	0	0	0	0	0	2,600	3,786.52

power and maintenance costs are considered, only 14 out of the 22 solutions can be utilized, as the other eight solutions advise the use of more than four pumps.

Although, the posted optimization problem of Jeddah's desalination plant appears simple with relatively few decision variables or constraints, the resulting solution space contains a variety of options for integer and noninteger feasible solutions. The procedure followed here is similar to large size optimization problems used worldwide [19,20]. Most importantly, the developed optimization formulation proved to be not only a powerful technique for solving mathematical programming problems, but also in generating optimal and feasible solutions of best operation policy in a given water production system setting, such as the Jeddah case. The developed solutions save huge quantities of desalinized water from wasting into the sea. Moreover, these solutions save both capital and total costs of operation.

3.5. Production tank

Production permeate tank is one of the decision variables in the optimization problem. Its size (1,000 m^3) was prespecified to account for the storage balance between inflow and outflow. As this tank is an essential component of the system, at least one tank is required to show in any feasible solution. Therefore, a constraint has been added to the formulation indicating that ($Q_{in} - Q_{out}$) must be less than or equal to 1,000 m^3. Almost all feasible solutions advise using only one tank. There is limited advice from feasible noninteger solutions to use portions (noninteger number) of tank size; however, this can be ignored in Jeddah's case. In some other cases, for example, in a newly constructed production system, it is recommended to release the storage constraint and allow as many tanks as needed to ensure optimality (cost minimization) in all proposed system components including tanks.

4. Conclusions

Mathematical programming used here has proven to be a powerful technique not only in finding an optimal solution for a minimization problem, but also in generating a nearly optimal feasible solution of best operation policy in the given setting of a water production system. The technique was capable of computing the operation cost of any given scenario in the solution space under the shutdown condition of any operating pump. This process led to an efficient analysis of all possible operation scenarios vs. cost. The split of the minimization problem into inclusion and exclusion of power and maintenance costs produced two different optimal solutions, thereby indicating a sensitivity of the operation strategy to the capital and total costs. The noninteger number of pumps that was obtained under the noninteger optimal solutions was viewed as an integer number with an equivalent production rate that can be customized and manufactured to empower an additional 12–26% reduction in the costs. Besides the saving of operation and maintenance costs, the obtained solutions can be adopted to save huge quantities of water production from wasting into the sea, and hence promote best practice and management of water resources.

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