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# Optimal SWRO Network Synthesis and Design Assessment with Water Quality Insights

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The paper addresses the design optimization of seawater reverse osmosis (SWRO) systems using network superstructures to facilitate the exploration of alternative designs. Based on previous efforts, distinct SWRO 'design classes' are explored that are based on a hierarchy of network size and facilitate a segregated and strategic design search, which allow for structural and operational variables to be investigated. The superstructures incorporate models that predict the performance of SWRO membrane elements, based on data obtained from commercially available simulators developed by SWRO membrane manufacturers. The models allow for the consideration of multiple water quality parameters within the feedwater stream, thus enabling the tracing of all the different components throughout the network. A case study for a typical seawater feed quality is presented as an illustration, in which SWRO network designs for three different network water recovery scenarios and two permeate quality constraints developed.

## 1. Introduction

Reverse osmosis technologies have become increasingly recognized for their efficiency in water desalination applications, over the past two decades. The design of seawater reverse osmosis (SWRO) desalination systems can ideally be treated as a form of network synthesis problems. Many superstructure optimization approaches have been developed and applied to establish appropriate designs for such systems. El-Halwagi (1992) was the first to introduce the idea of reverse osmosis network synthesis using the State Space approach. Voros et al (1996) developed a modified representation for the State Space approach. Marriott and Sorensen (2003) used genetic algorithms to solve membrane network superstructures. Saif et al (2008) solved SWRO network superstructure problems using deterministic global optimization techniques. Former conventional representations generally determine a single optimal design solution, and thus the ability to demonstrate tradeoffs between distinctly structured and feasible design alternatives are often unheeded.

Therefore, this paper demonstrates the use of a previously developed systematic representation (Alnouri and Linke, 2012a) for seawater reverse osmosis (SWRO) network synthesis, which in turn allows for design exploration based on a synchronized concept of process superstructures. Multiple lean superstructures that allow the assessment of structural and operational variants within each design class were systematically investigated. The overall purpose is to allow for the extraction of multiple distinct optimal designs through global optimization. In doing so, distinctive design alternatives in terms of connectivity and RO unit placement were generated and explored. As a result, an insightful and improved evaluation of the various design classes were easily made, by exploring the design space, as well as trade-offs between network complexity and design effectiveness.

## 2. Design Assessment Framework

This work exploits the various design class categories that have been previously presented by Alnouri and Linke (2012a). The different options available for RO unit placement (e.g. a stage or pass arrangement), and the connectivity associated with each possibility, allow structural and operational variations to be selectively examined for different scenarios. Each design class involves a set of both 'enforced' and

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‘optional’ connectivity (Alnouri and Linke, 2012a). Enforced connections consist of all streams associated with achieving the desired arrangement of RO units. Optional connections on the other hand involve any bypass or recycle streams that could potentially be capable of enhancing the design performance. Figure 1 below summarizes RO unit arrangements, as well as the corresponding lean superstructures, for single unit, two-unit and three-unit design class alternatives.

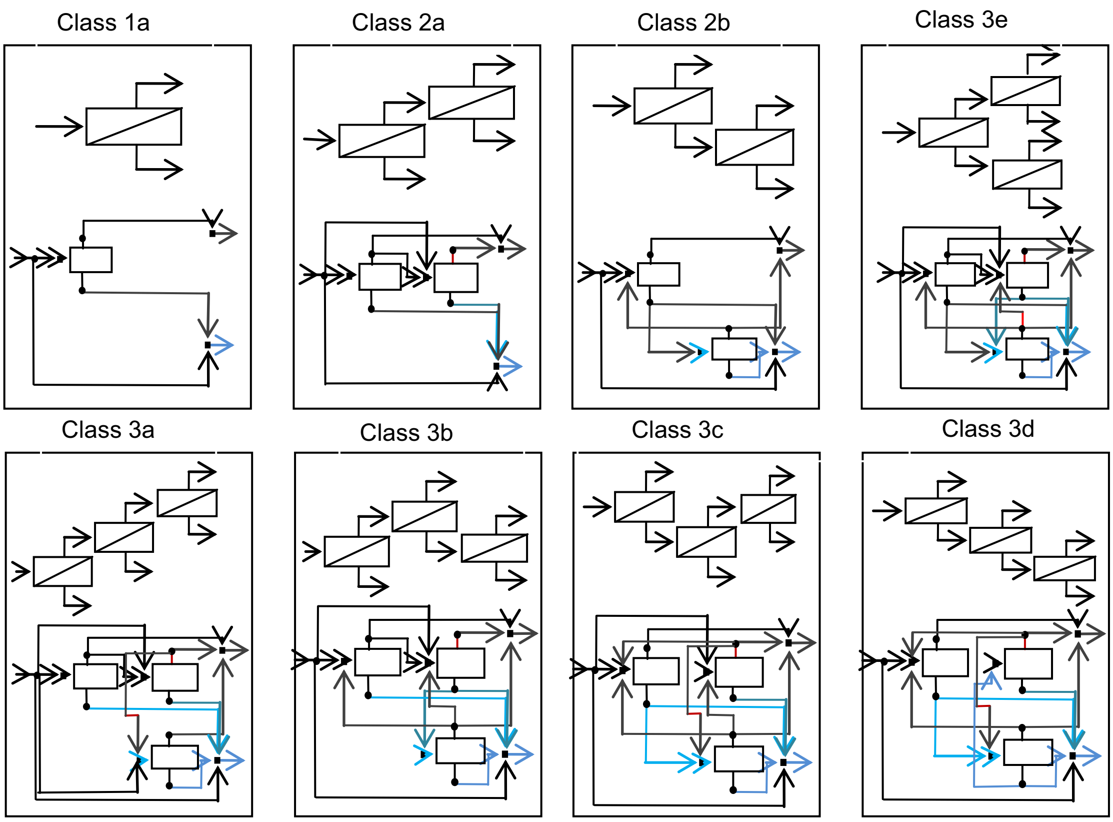



*Figure 1: RO unit arrangements, and corresponding lean superstructures, for single unit, two-unit and three-unit design class options (Alnouri and Linke, 2012a).*

## 3. Water Quality Parameters

Detailed water quality information is considered by accounting for individual seawater constituents. To this end, the superstructure models include membrane element models that enable the prediction of the performance of commercial seawater reverse osmosis membrane elements. Accounting for all constituents allows the tracing of all the different seawater components throughout the network after pretreatment, and provides more significance to the solutions extracted (Alnouri and Linke, 2012b) as compared to the typical processing of lumped salinity information in the form of Total Dissolved Solids (TDS) that is usually employed in SWRO process network optimization. In particular, this work utilizes models that have been developed via the use of ROSA Software (Reverse Osmosis Systems Analysis), which assists in the design of systems operating using DOW FILMTEC™ membrane elements.

## 4. Problem Formulation and Implementation

The formulation of this problem results in of a Mixed Integer Non Linear Program (MINLP), which includes both total and component mass balances for all membrane units, stream splitters, and mixers within the network (Alnouri and Linke, 2012a). Additionally, constraints associated with handling and placements of pressure controlling devices are included. The design objective is to minimize the cost of water produced. The detailed economic assessment captures all significant capital and operating expenses that are typically associated with intake, pre and post treatment in SWRO systems and is based on Wilf (2007), besides utilizing desired process conditions and constraints in the problem formulation. The problem is implemented in MS Excel using “what’sBest” by LINDO, an Excel Add-In Solver for Linear, Non-linear, and Integer Modeling, thus facilitating the use of reasonably simple interface for the execution of the problem.

## 5. Case Study

An illustrative case study has been carried out, in which a Typical Seawater quality was used as feed into the network synthesis problem (Lenntech, 2005). The capability of obtaining solutions for each feasible design class scenario is demonstrated, based on all provided input data. Table 1 summarizes all main input parameters used in this case study. Three different water recovery scenarios have been imposed on the system (30 %, 40 % and 50 %), subject to two different permeate quality constraints (500 ppm and 150 ppm). Tables 2 presents capital, operating and total annualized costs per $m^3$ of water produced for all attainable design classes that have been observed. It can be noted that design classes 1a, 2a and 3a were unable to attain a solution that achieves a permeate with a 500 ppm TDS specification, and all three in addition to class 2b become infeasible when the more stringent permeate specification (150 ppm) was utilized.

*Table 1: Case study parameters*

| Parameter | Value |
|---|---|
| Product Water Flowrate | 0.09259 $m^3/s$ |
| Water Recovery | 30 % \| 40 % \| 50 % |
| Inlet Feedwater Pressure | $10^5$ Pa |
| Outlet Permeate Pressure | $10^5$ Pa |
| Maximum allowable concentration of TDS in the outlet permeate stream (after post-treatment) | 500 ppm \| 150 ppm |
| Membrane Element Type | SW30HRLE – 440i |
| Temperature | 35 °C |
| Depreciation | 20 y |
| Power cost | 0.05 $/kW h |

*Table 2: Capital, Operating, and Total costs per $m^3$ of water produced for feasible design class solutions*

| | R=30 % 500 ppm | R=40 % 500 ppm | R=50 % 500 ppm | R=30 % 150 ppm | R=40 % 150 ppm | R=50 % 150 ppm |
|---|---|---|---|---|---|---|
| Class 1a (¢/$m^3$) | Infeasible | Infeasible | Infeasible | Infeasible | Infeasible | Infeasible |
| Class 2a (¢/$m^3$) | Infeasible | Infeasible | Infeasible | Infeasible | Infeasible | Infeasible |
| Class 2b (¢/$m^3$) | 76.94 | 61.60 | 52.43 | Infeasible | Infeasible | Infeasible |
| Class 3a (¢/$m^3$) | Infeasible | Infeasible | Infeasible | Infeasible | Infeasible | Infeasible |
| Class 3b (¢/$m^3$) | 77.86 | 62.40 | 53.18 | 87.71 | 72.25 | 63.03 |
| Class 3c (¢/$m^3$) | 77.51 | 62.16 | 52.95 | 87.60 | 72.44 | 63.26 |
| Class 3d (¢/$m^3$) | 80.01 | 64.45 | 55.52 | 89.87 | 74.60 | 65.36 |
| Class 3e (¢/$m^3$) | 77.91 | 62.48 | 53.24 | 88.01 | 72.56 | 63.30 |

It was found that since the feed flowrate into the system was kept as a variable in each case, increasing the water recovery within the network while specifying a fixed value for product water flow would reduce each of the capital, operating and total costs of feasible designs, due to a decreased input flowrate into the system. As a result, all feed flowrate dependent costs declined (such as site preparation, intake, pretreatment, as well as other capital and operating expenses). According to the results presented in Table 2, all cases involving a permeate constraint of 500 ppm yield a Class 2b optimal solution as the best performing design amongst all feasible ones, for the three different water recovery conditions. Class 2b was found to be infeasible when a more stringent permeate quality constraint was used instead. Consequently, the best performing design classes amongst all feasible ones were Class 3c, for the lowest water recovery case (30 %), and Class 3b for the 40 % and 50 % water recovery scenarios.

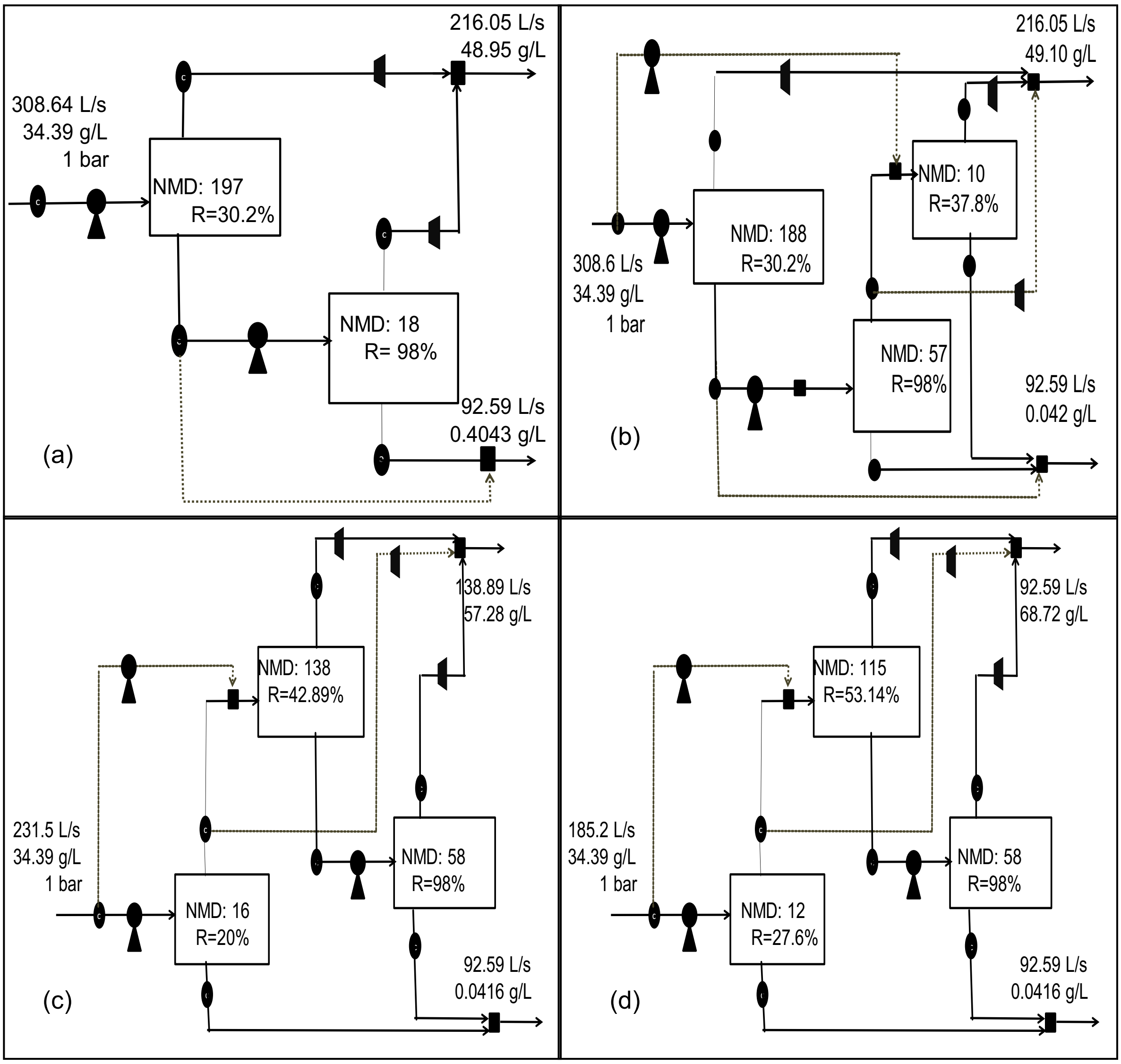
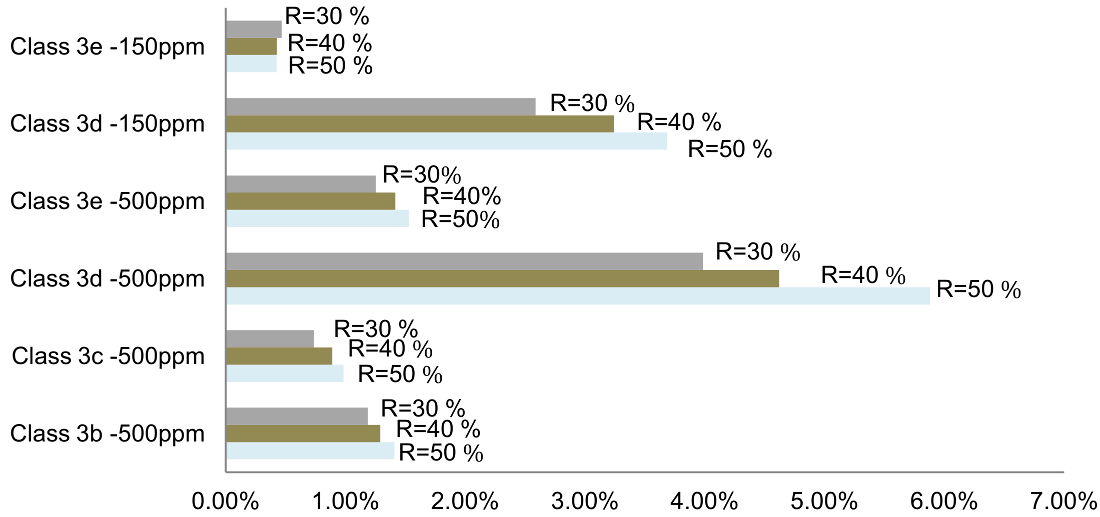



*Figure 2: Summary of the best performing feasible design class solutions, for a Typical Seawater Feed case. (a) R= 30 %, and 500 ppm water quality specification (b) R= 30 %, and 150 ppm water quality specification, (c) R= 40 %, and 150 ppm water quality specification, (d) R= 50 %, and 150 ppm water quality specification*

Figure 2 below illustrates and compares all feasible design class solutions that yield the best performance in terms of total cost per $m^3$ of water produced, according to the different specifications for water recovery and permeate quality that have been employed. Water recoveries per RO unit, as well as details for the required numbers of modules are presented in each figure illustrated. It can be noted that percentage recoveries achieved within RO passes that are coupled with further treatment of permeate streams, are always relatively higher compared to the remaining units within the network. As demonstrated, the more relaxed permeate quality case (500 ppm) identifies two-unit Class 2b designs to be superior to other feasible designs, for all water recovery scenarios. Imposing more stringent permeate quality specifications causes a shift towards higher design class solutions. An illustration for Class 3c solutions for the 30 % water recovery case, and Class 3b solutions for both 40 % and 50 % water recoveries are illustrated below.




| | Class 3b - 500ppm | Class 3c - 500ppm | Class 3d - 500ppm | Class 3e - 500ppm | Class 3d - 150ppm | Class 3e - 150ppm |
|---|---|---|---|---|---|---|
| R=30% | 1.19% | 0.74% | 3.98% | 1.25% | 2.59% | 0.47% |
| R=40% | 1.29% | 0.89% | 4.62% | 1.42% | 3.24% | 0.43% |
| R=50% | 1.41% | 0.98% | 5.88% | 1.53% | 3.69% | 0.42% |

*Figure 3: Comparison amongst all obtained feasible design class solutions, relative to the best performing design*

Figure 3 shows the percentage differences in objective function values between the best performing designs (Class 2b in the case of 500 ppm specification, and Classes 3b and 3c in the case of 150 ppm specification), based on the total annualized costs obtained for all other feasible designs that were generated. According to the case study findings, Class 3c achieves the least deviancy (0.74 % - 0.98 %) from the target solutions for the 500 ppm specification, whereas Class 3e provides the smallest percentage differences, with a range of 0.42 % - 0.47 % from each target cost. On the other hand, Class 3d always had the highest differences compared to the best performing target, requiring an extra 3.98 %-5.88 %, and 2.59 % - 3.69 % in each case as additional cost. Tables 3 and 4 present detailed stream information for permeate and concentrate streams of several solutions extracted.

*Table 3: Water quality information for both permeate (network outlet and post treatment) and brine concentrate, (Class 2b, and 3c solutions)*

| | Typical Seawater Feed (mg/L) | Network Permeate (mg/L) | Post-treatment Permeate (mg/L) | Network Concentrate (mg/L) | Network Permeate (mg/L) | Post-treatment Permeate (mg/L) | Network Concentrate (mg/L) |
|---|---|---|---|---|---|---|---|
| | (Lenntech, 2005) | Class 2b R=30 % 500 ppm | Class 2b R=30 % 500 ppm | Class 2b R=30 % 500 ppm | Class 3c R=30 % 150 ppm | Class 3c R=30 % 150 ppm | Class 3c R=30 % 150 ppm |
| K | 380 | 6.84 | 6.84 | 539.92 | 0.7704 | 0.7704 | 542.53 |
| Na | 10,556 | 136.03 | 136.03 | 1,5021 | 14.0 | 14.0 | 1,5074 |
| Mg | 1,262 | 3.27 | 10.0 | 1,801 | 0.2715 | 10.0 | 1,802 |
| Ca | 400 | 1.035 | 30.0 | 570.98 | 0.086 | 30.0 | 571.39 |
| Sr | 13 | 0.0318 | 0.0318 | 18.55 | 0.0026 | 0.0026 | 18.57 |
| $CO_3$ | 0 | 0 | 59.99 | 0 | 0 | 68.8 | 0 |
| $HCO_3$ | 140 | 2.91 | 2.91 | 198.75 | 0.3429 | 0.3429 | 199.85 |
| $SO_4$ | 2,649 | 6.86 | 6.86 | 3,781 | 0.5698 | 0.5698 | 3,784 |
| Cl | 18,985 | 247.34 | 247.34 | 27,015 | 25.51 | 25.51 | 27,110 |
| Sum | 34,385 | 404.32 | 500 | 48,948 | 41.55 | 150 | 49,104 |

*Table 4: Water quality information for both permeate (network outlet and post treatment) and brine concentrate, (Class 3b solutions)*

| | Typical Seawater Feed (mg/L) | Network Permeate (mg/L) | Post-treatment Permeate (mg/L) | Network Concentrate (mg/L) | Network Permeate (mg/L) | Post-treatment Permeate (mg/L) | Network Concentrate (mg/L) |
|---|---|---|---|---|---|---|---|
| | (Lenntech, 2005) | Class 3b R=40% 150 ppm | Class 3b R=40% 150 ppm | Class 3b R=40% 150 ppm | Class 3b R=50% 150 ppm | Class 3b R=50% 150 ppm | Class 3b R=50% 150 ppm |
| K | 380 | 0.7682 | 0.7682 | 632.82 | 0.7683 | 0.7683 | 759.23 |
| Na | 10,556 | 14.0 | 14.0 | 17584 | 14.0 | 14.0 | 21,098 |
| Mg | 1,262 | 0.2738 | 10.0 | 2,103.15 | 0.2737 | 10.0 | 2,523 |
| Ca | 400 | 0.0868 | 30.0 | 666.61 | 0.0868 | 30.0 | 799.91 |
| Sr | 13 | 0.0027 | 0.0027 | 21.66 | 0.0027 | 0.0027 | 26.00 |
| $CO_3$ | 0 | 0 | 68.8 | 0 | 0 | 68.80 | 0 |
| $HCO_3$ | 140 | 0.3415 | 0.3415 | 233.11 | 0.3415 | 0.3415 | 279.66 |
| $SO_4$ | 2,649 | 0.5747 | 0.5747 | 4,414 | 0.5746 | 0.5746 | 5,297 |
| Cl | 18,985 | 25.52 | 25.52 | 31,625 | 25.52 | 25.52 | 37,945 |
| Sum | 34,385 | 41.56 | 150 | 57,281 | 41.56 | 150 | 68,729 |

## 6. Conclusions

This study involves the optimization of SWRO desalination networks using superstructures that facilitate the exploration of alternative designs. Models that predict the performance of SWRO membrane elements were used, based on data obtained from available commercial SWRO simulators, which allow multiple water quality parameters to be considered within the feedwater stream. A case study for a typical seawater feed quality is presented as an illustration, in which SWRO network designs for three different network water recovery scenarios and two permeate quality constraints developed. An illustrative case study involving a Typical Seawater feed quality has been presented. All of the different scenarios that have been considered were based on three specified water recoveries (30 %, 40 % and 50 %) as well as two different permeate quality constraints (500 ppm and 150 ppm). A two-unit solution was found for all cases involving a 500 ppm permeate quality constraint, whereas all 150 ppm cases shifted to higher design class solutions (Class 3c, for the 30 % water recovery case, and Class 3b for the 40 % and 50 % water recovery scenarios).

### References


Alnouri S.Y., Linke P., 2012a, A systematic approach to optimal membrane network synthesis for seawater desalination, J. Membr. Sci. 417–418, 96-112

Alnouri S.Y., Linke P., 2012b, Optimal Membrane Desalination Network Synthesis with Detailed Water Quality Information, Comput. Aided Chem. Eng., 31, 520-524

El-Halwagi M., 1992, Synthesis of reverse osmosis networks for waste reduction, AIChE J. 38 (8), 1185–1198.

Lenntech, Major ion composition of seawater, 2005, Water Condition & purification < www.lenntech.com/composition-seawater.htm> accessed 15.02.2013

Marriott J., Sorensen E., 2003, The optimal design of membrane systems, Chem. Eng. Sci. 58, 4991–500

ROSA Software, Dow Water & Process Solutions <www.dowwaterandprocess.com/support_training/design_tools/rosa.htm> accessed 18.02.2013

Saif Y., Elkamel A., Pritzker M., 2008, Optimal design of reverse-osmosis networks for wastewater treatment, Chem. Eng. Process. 47, 2163–2174

Voros N., Maroulis Z.B., Marinos-Kouris D., 1996, Optimization of reverse osmosis networks for seawater desalination, Comput. Chem. Eng. 20, 345–350.

What'sBEST! - Excel Add-In for Linear, Non-linear, and Integer Modeling, <www.lindo.com/index.php?option=com_content&view=article&id=3&Itemid=11>accessed 19.02.2013

Wilf, M., 2007, The Guidebook to Membrane Desalination Technology: Reverse Osmosis, Nanofiltration and Hybrid Systems: Process Design, Application and Economics. Balaban Desalination Publications, L'Aquila, Italy