Decision Support System for Optimal Planning of Wastewater Treatment Systems

Mariam Abu Wasel Egbariah

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE MASTER'S DEGREE

University of Haifa

Faculty of Management

The Department of Natural Resources and Environmental Management

November, 2016

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(Chairperson of Master's studies Committee)

Dedication

I dedicate this thesis

to my supervisors, my beloved husband Mustafa and my precious family

Acknowledgments

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Mariam Abu Wasel Egbariah

Abstract

Water scarcity, uneven allocation of water resources among the different sectors, global warming, population and urban growth are pushing many countries around the world, especially in arid and semi-arid regions like Israel, to search for alternatives for water resources. Special attention is given to treated wastewater which is mainly used in agriculture for irrigation, but there are many challenges, such as health issues, soil and groundwater contamination due to irrigation with effluents (Ahmadi and Merkley, 2009). At the same time, water and wastewater treatment systems are complex and changing forward within new technologies (MWH, 2005).

The main focus of this thesis is to develop and test an optimization model that selects the treatment processes which are to be included in a treatment train (i.e. sequence or series of treatments) of the Waste Water Treatment Plant (WWTP) for an effluent stream which has a given stream size, inflow quality parameters and required quality standards in its effluents. A "solution" on the treatment side is a train (sequence, series) of treatment technologies, which minimizes the total cost subject to given quality standards, physical, operational and technological constraints. We developed two models for optimal design of wastewater treatment train: the Five-Stages Model and Unlimited Stages Model. The Five-Stages Model has five stages of treatment: 1) Preliminary, 2) Primary, 3) Secondary, 4) Tertiary, and 5) Disinfection. For each stage, a single treatment technology is chosen. Unlike the Five-Stages Model, the Unlimited Stages Model describes selection of treatment train technologies without taking into consideration the treatment stages.

As a secondary product of this thesis, and building on the treatment train optimization model, we have also developed a regional planning model of wastewater treatment, conveyance and storage system. This model takes into consideration the design and layout problem for optimizing a distribution network for the treatment facilities of wastewater and the conveyance/storage of treated wastewater to consumers.

Base Runs and Sensitivity Analysis runs were conducted for the different models to test how the optimal design changes with different system parameters, such as the effluent quality standards, and the damage cost functions for low effluent quality. Our results indicate that the models

developed herein can help in making decisions related to the impact of various quality effluents on the system design and allow for optimal planning of reclaimed water systems while accounting for physical, technological and environmental considerations.

Note: The physical and economic data used in this thesis are taken from various sources, and are not claimed to be representative of any specific source of urban sewage with its quality, nor are the required quality parameters of the effluent universal. The results presented herein are therefore to be viewed as indicative and not definitive. The DSS is designed to be populated with real data by its user.

Keywords: Decision Support System; Optimization; Regional Planning; Wastewater Treatment; Reclaimed Water

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List of Symbols

D – Pipeline diameter (mm)

Q_{avg} - Average flow (m^3/day)

y_j - Binary variable presenting the selected technology

DC - Damage Cost ($/year)

$C_{\min}$ - Minimum pipeline depth (m)

NS - Number of Stage

NT_s - Number of technologies available at stage s

L_w - Pipe excavation width (m)

$KWHC$ - Pumping Cost ($\$/kwhr$)

XP - The total head difference (m)

ΔZ_p - Topographical difference (m)

TC - Total Cost ($/year)

C_{pg1} and C_{pg2} - Construction costs for shallow and deep excavation ($/year) respectively

A_s - Annual cost of 1 m^3 excavation

$CC^{capital}$ - Capital Cost ($/year)

$CC^{O\&M}$ - Operation and Maintenance Cost ($/year)

DC^k - Damage Cost for quality parameter k

Q_{dwf} - Dry weather flow (m^3/day)

CP_{energy} - Energy Cost ($/year)

ΔHf - Energy Head Loss (m)

Q - Flow (m^3/season)

$Q_{\max}^{V_{\max}}$ - Flow capacity according to the maximum velocity restriction

$Q_{\max}^{A}$ - Flow capacity according to the partially full pipe restriction

D_p - Link/ Pumped pipeline diameter (cm)

A_2 - Matrix of M-N2 dependent columns of matrix A

A_1 - Matrix of N2 independent columns of matrix A

$J_{\max}$ - Maximum hydraulic gradient (m/m)

w - Number of pumping hours $(hr/season)$

NT - Number of Technology

Q_{pday} - Peak daily flow (m^3/hr)

C_{Cpump} - Pump station Construction Cost ($/year)

C_{pp} - Pumped pipeline Capital Cost ($/year)

Cr - Reservoir Capital Cost ($/year)

Cor - Reservoir Operation and Maintenance Cost ($/year)

V_{res} - Reservoir Volume (m^3/year)

T_s - Selected technology for each stage s

$F(y_{\forall j})$ - Represent the assembly rules constraints

f_{T_s} - The performance function of technology T_s

$G(y_{\forall j})$ - Represent a constraint for one selected technology for each stage

Q_{dep} - Vector of dependent flow variables

Q_{indep} - Vector of independent decision flows

WQ_s^k - Water quality, for stage k and technology s

C - Hazen Williams coefficient ($-$)

L_p - Pumped pipeline length (km)

L_g - Gravitational pipeline length (km)

A - Cross sectional area of the flow (m^2)

A_1 and A_2 - Excavation areas to and above a depth of H1 (m^2), respectively

T_{prel} and T_{prim} - Integer variables that determine the selection between the alternative technologies for each stage

H1 - Least excavation depth cost (m)

J - Pipeline slope (m/m)

J_s - Soil surface slope (m/m)

N - Manning coefficient, a property of the pipe material

P – Wetted perimeter (m)

Q - Discharge (m^3/sec)

R =A/P- The hydraulic radius (m)

ν - Flow velocity (m/sec)

1. Introduction

Water scarcity, uneven allocation of water resources among the different sectors, global warming, population and urban growth are pushing many countries around the world, especially in arid and semi-arid regions like Israel, to search for alternatives for water resources. Special attention is given to treated wastewater which is mainly used in agriculture for irrigation, but many challenges arise, such as health issues, soil and groundwater contamination due to irrigation with effluents (Ahmadi and Merkley, 2009). At the same time water and wastewater treatment systems are complex and are changing with the advent of new technologies (MWH, 2005).

In 1953 Israel had the first regulations and standards for the reuse of treated effluents. However, until 1970, the reuse of treated wastewater in the country was based mainly on small separated projects without a clear policy. Since the beginning of the 70's, Israel has implemented a planned and intensive use of treated wastewater for irrigation, today the reuse of treated wastewater for irrigation is about 75% of total produced wastewater, when most of the reclaimed water use is in agriculture. Reclamation of wastewater is accomplished by 135 Wastewater Treatment Plants (WWTP), which treat approximately 355 Million Cubic Meters (MCM) per year. This amount represents approximately 31% of the water supplied to agriculture and 18% of water supplied throughout the country to all consumer sectors. The goal of the Water Authority is to utilize 95% of the treated wastewater for various uses within the coming 5 years (Israeli Water Authority). The increase of using treated wastewater over the past years increased the awareness of this issue, including the awareness of the environmental effects arising from the irrigation with treated wastewater. Thus, the regulations are becoming stricter and require compliance with certain values of the different quality parameters; this in turn motivates the adoption of new and more advanced wastewater treatment technologies to get effluents with higher quality to reduce the environmental damage that may occur as a result of the continuous irrigation with treated water.

The treatment processed can be divided into different stages:

1) Preliminary
2) Primary (usually mechanical): treatment is designed to remove gross, suspended and floating solids from raw sewage.
3) Secondary (usually biological): treatment to remove the dissolved organic matter that escapes the primary treatment. About 85% of the suspended solids and BOD can be removed by a well running plant with secondary treatment.

4) Tertiary treatment (advanced treatment): this treatment can remove more than 99 percent of all the impurities from sewage, producing an effluent of almost drinking-water quality. The related technology can be very expensive, requiring a high level of technical know-how and well trained treatment plant operators, a steady energy supply, and chemicals and specific equipment which may not be readily available.
5) Disinfection, typically with chlorine, can be the final step before discharge of the effluent.

The main focus of this thesis is to develop and test an optimization model that selects the treatment processes which are to be included in a treatment train (i.e. sequence or series of treatments) of the Waste Water Treatment Plant (WWTP) for an effluent stream which has a given stream size, inflow quality parameters and required quality standards in its effluents. A "solution" on the treatment side is a train (sequence, series) of treatment technologies, which minimizes the total cost subject to given quality standards, physical, operational and technological constraints. Section 3.1 presents two models for optimal design of wastewater treatment train the Five-Stages Model and Unlimited Stages Model.

The Five-Stages Model has five stages of treatment: 1) Preliminary, 2) Primary, 3) Secondary, 4) Tertiary, and 5) Disinfection. For each stage, a treatment technology should be chosen. The model has two formulations to describe the selection of the treatment technology; one is based on binary decision variables, while the second is based on integer variables (1-44). The unlimited stage model, unlike the previous model, describes selection of treatment train technologies without taking into consideration the treatment stages. That is, choosing the treatment technology is based on the treatment technologies we have on the knowledge database.

In order to test these models, typical physical and economic data are used, without claiming to be relevant or accurate to any specific real case. A Base Run and Sensitivity Analysis runs are presented in Sections 3.1.5 and 3.1.7. The purpose of these runs is to test how the model and the selection of treatment train technology are affected by changing the effluent quality parameters concentration, how is this reflected in the total cost, and how does the damage cost function affect the selection of treatment train technologies.

As a secondary product of this thesis, and building on the treatment train optimization model in Section 3.1, we have also developed a regional planning model of wastewater treatment, conveyance and storage system. This model takes into consideration the design and layout problem for optimizing a distribution network for the treatment facilities of wastewater and the conveyance/storage of treated wastewater to consumers. This regional model and its preliminary results are given in Section 3.2.

1.1. Motivation

Water scarcity in arid and semi-arid regions, such as Israel, makes the challenge for water management a first priority. Water management is about maximizing productivity under economic and environmental constraints including protection of soil and water resources (Shani et al., 2007). Therefore, this work concentrates on wastewater management and regional planning of wastewater treatment and distribution. In 2015, 96% of the Israeli collected sewage was treated in wastewater treatment plants (WWTP). In addition, today the reuse of treated wastewater for irrigation is about 75% of total produced wastewater, where most of the reclaimed water use is in agriculture (Israeli Water Authority).

In light of the above, there is a need for planning and developing a Decision Support System (DSS) which aims at helping decision makers and engineers to determine optimal decisions regarding planning new WWTPs and upgrading existing ones. This DSS should be able to provide guidance on the technologies that should be used and the optimal distribution system which should be built to deliver the effluents with minimum cost.

1.2. Objectives and Contribution

The objective of this research is to develop a DSS for wastewater treatment systems planning and design using optimization methods in order to help and guide long-term reclaimed water use and treatment. Following a literature review, we found that there is value in developing such a DSS, which combines the selection of treatment technologies and delivery system of reclaimed water in one platform.

The two models developed in this research: the DSS for optimal treatment train design and the regional planning model for the wastewater and effluent conveyance system will help in making decisions related to the impact of various quality effluents for agriculture economy and will allow efficient use of reclaimed water, taking into account the physical, technological and environmental considerations.

The developed models are generic and flexible enough to allow engineers and planners to use their own information and specific data, in order to test tradeoffs, different treatment train technologies, different effluent quality and its environmental effluences, and different allocations of different effluent qualities. The models are flexible for different sets of input data and transparent enough to convey to the decision makers the full range of consequences of different possible decisions.

2. Literature review

The literature review in this work surveys publications on planning and management of sewage treatment systems, to identify and study similar studies and projects on planning and management of systems for treatment of wastewater and reuse of the effluents. We covered literature in four topics which are of importance to our study:

1. Wastewater treatment technologies;
2. Implication of reclaimed water irrigation on the crop yield and quality;
3. Regional wastewater treatment and reuse planning and management;
4. Decision Support Systems of wastewater treatment and reuse systems

The following Sections detail each of these topics.

2.1. Wastewater Treatment Technologies

Designing a wastewater treatment train depends on a number of factors, such as influent quality, regulatory requirements, consumer requirements, environmental concerns, construction challenges, operational constraints, available treatment technologies, and economic feasibility (MWH, 2005).

Cost modeling, in general, helps us, as engineers and decision makers, to understand the operating and maintenance cost structure of WWTPs and provide a detailed and scientifically strict approach for planning of new facilities, as well as assisting in evaluations of the true potential of water reuse projects. Modeling is useful for comparing different treatment technologies from an economic perspective (Jödicke et al., 2001). The WWTP volume has a large influence in the determination of the operating and maintenance costs, while other parameters, such as plant age and pollutant removal efficiency, are important in terms of explaining the costs (Hernandez-Sancho et al., 2011).

Besides the WWTPs volumes, regional considerations of effluents transfer and allocations are another important issue to consider. Determining regional allocations of wastewater is based on calculating the net benefits of irrigation in different areas. In one such study, a linear programming optimization model was applied for various levels of environmental hazards, which simultaneously determines the combinations of agricultural crops to be irrigated, water sources and allocation for different regions (Haruvy, 1998).

While there are a number of such studies, the need arises to consider the uncertainties that arise in dealing with a typical modelling project, by preparing a list of sources of uncertainty and considering them in engineering projects (Belia et al., 2009).

2.2. Uses of Reclaimed Wastewater

Water is becoming scarce not only in arid and drought areas but also in regions where rainfall is abundant: water scarcity concerns the quantity of the available resource and the quality of the water because degraded water resources become unavailable for more stringent requirements. Therefore, there is a need to use lower quality waters in irrigation management and practice (Pereira et al., 2002).

Shaviv et al. (2009) argued that using reclaimed wastewater for agriculture irrigation, has its benefits but also some drawbacks. The benefits come as values of conservation, waste recycling and re-use of nutrients. The drawbacks are because using reclaimed wastewater for irrigation exposes human beings and the environment, as soil, water, and plants to salinity problems, accumulation of Boron, sodification and damage to structure, potential N and P accumulation in soil and groundwater, undesired effects of organic constituents and health risk by pathogens. Salinity is one of the greatest concerns in using reclaimed wastewater, due to using more conventional and prevalent treatment technologies, which do not apply salt separation techniques.

The challenge for reclaimed water management is to maximize productivity under economic and environmental constraints including protection of soil and water resources. The model by Shani et al. (2007) takes into consideration as many of the essential factors of the soil-plant-atmosphere system in a closed form solution. The model integrates plant performance under various environmental, biological and management parameters. Coping with water scarcity requires measures and policies of water management that may be grouped into two main categories: demand and supply management (Pereira et al., 2002).

2.3. Distribution Systems of Reclaimed Water

A variety of methodologies have been proposed for obtaining optimal distribution system designs by simultaneously addressing the layout (topology) and sizing of components.

A two-level hierarchically integrated system of models for the layout of single and multiple source water distribution systems, where a non-linear programming model is used to select an economical tree layout for major pipe links and an integer programming model adds the loopforming links to satisfy a specified level of reliability (Rowell and Barnes, 1982). In another approach, two linked linear programs were developed, where one solved the layout and the other determined the leas-cost components' sizes (Morgan and Goulter, 1982). Further improvements to these approaches were made by Lansey and Mays (1989) and Duan et al. (1990), who included sizing and location of pumps, storage tanks, and valves as well as pipes in the optimization. Alperovits and Shamir (1977) adopted the split pipe approach regarding to pipe sizing, and further expanded the methodology by considering multiple loading conditions and by including the sizing of pumps, location of valves and sizing of operational reservoirs in the optimization.

Cembrowicz (1992) developed a two-step approach, used a GA model to determine the optimal layout and LP for determining the least-cost pipe diameters. A GIS-based DSS called WADSOP was developed by Taher and Labadie (1996), in which an NLP-based network solver and an LP-based optimal design model are used interactively in a convergent scheme to determine least-cost design, including the layout. Tanyumboh and Sheahan (2002) employed a maximum entropy based approach in considering jointly layout, reliability and pipe sizing optimization problem. Finally, Hassanli and Dandy (2005) used a GA approach for optimum layout and optimum hydraulic design of a branched pipe network.

2.4. Decision Support Systems

Wastewater and effluents pipelines and treatment plants systems optimization is an emerging discipline. Most of the modeling optimization is concentrated on either the sewer pipeline system or the treatment plant. The problem that engineers face while designing a regional wastewater and delivery system with treatment plants and a linking network is the design and operation of links and how the treated wastewater will be transported to a main concentration point for centralized transmission (Brand and Ostfeld, 2011). Despite the difficulties that engineers face and the complexity of the integrative management modeling; it is an essential tool for determining the optimal treatment and reuse of wastewater. A wide view of all related issues allows accounting for all factors, for the benefit of whole community (Oron, 1996).

A decision support system (DSS) is an information system that supports a user in choosing a consistent, optimal or, at least, near-optimal solution for a particular problem (Poch et al., 2004). Developing a DSS for water and wastewater treatment process selection and design requires a structured framework. The scope of the DSS, the purpose of its construction, and the elements considered are the main factors that should shape and affect the way a DSS is constructed

(Hamouda et al., 2009). Having a DSS can help to advance innovation and aid communities in meeting their sustainability goals, once it is fully developed. Such a DSS can help decision makers to explore the design space of sustainable wastewater solutions that is relevant for their particular context, and identify solutions that balance environmental, economic and social needs (Chamberlain et al., 2014).

A DSS is a good tool for comparing a wide variety of systems with respect to a multi-disciplinary set of sustainability indicators (Balkema et al., 2001). An integer programming model has been used to identify sustainable treatment options for domestic wastewater using a weighted sum of sustainability indicators in the objective function (Balkema et al., 2001). Another method - the Analytical Hierarchy Process (AHP) - has been used for selecting wastewater treatment technologies by Addou et al. (2004) and Bick and Oron (2004). A decision support system of multi-criteria analysis was developed by Hidalgo et al. (2007) to promote safe urban wastewater reuse.

A Nonlinear Chance Constrained Stochastic Programming model for integrated water system optimization, is accounting for water quantity and quality from different sources for different uses with different costs. Genetic algorithm (GA) was applied to achieve the minimum Total Cost (TC) and maximum Satisfying Probability (SP) of water system equilibrium (Huang et al. 2013). This optimization model is applied to Beijing, China, and presents a general solution of water planning and reclaimed wastewater allocation for policy makers to generate decision alternatives and identify desired policies and water planning under various socio-economic conditions. The decision system evaluates the feasibility of implementing integrated wastewater reuse projects through the selection of appropriate treatment trains that will produce effluent of the required reuse quality (Adewumi et al., 2010).

Having conflicting objectives, such as minimizing the cost and maximizing the performance, makes the evaluation and the selection of treatment process more complex. Thus, there is a need for systematic approaches using decision systems or models to help in the selection of appropriate treatment trains for given reuse. The WAWTTAR model (Finny and Gearheart, 1998) provides decision support for evaluation and selection of appropriate Treatment Technologies (TTs) suggested by the user for developing countries. Another model called MOSTWATAR (Dinesh and Dandy, 2003) stands for Model for the Optimum Selection of Technologies for Wastewater Treatment and Reuse. This model was developed to assist planners and decision makers in the techno-economic assessment of reclamation technologies and to aid in the selection of the best five treatment technologies for a given case.

An integrated DSS for Water Treatment for Reuse with Network Distribution (WTRNet) has been developed within the AQUAREC project on “Integrated Concepts for Reuse of Upgraded Wastewater”, under the Fifth European Community Framework Program (Joksimovic et al., 2008, Joksimovic, 2006). This DSS provided an integrated framework optimization of treatment and distribution aspects of water reuse and the selection of end-users. The model is aimed to combine both the process synthesis and water distribution aspects of reuse, and to overcome some of the limitations that appear in currently available decision support tools.

3. A DSS for Optimal Design of Wastewater Treatment Systems

The main focus of this thesis is to develop and test an optimization model that selects the treatment processes which are to be included in a treatment train (i.e. sequence or series of treatments) of the Waste Water Treatment Plant (WWTP) for an effluent stream which has a given stream size, inflow quality parameters and required quality standards in its effluents. A "solution" on the treatment side is a train (sequence, series) of treatment technologies, which minimizes the total cost subject to given quality standards, physical, operational and technological constraints. Section 3.1 presents two models for the optimal design of wastewater treatment train.

As a secondary product of this thesis, and building on the treatment train optimization model in Section 3.1, we have also developed a regional planning model of wastewater treatment, conveyance and storage system. This model takes into consideration the design and layout problem for optimizing a distribution network for the treatment facilities of wastewater and the conveyance/storage of treated wastewater to consumers. This regional model and its preliminary results are given in Section 3.2.

At the early stages of the research we investigated different tools for implementation of the models which will be developed in this study. The options included:

1. An Excel-based model: the advantages of using Excel include rapid development and universal access to the software. Difficulties in using Excel may arise due to the specific forms of the mathematical expressions in the objective function and/or constraints, such as non-linearity and discrete variables.
2. Acquisition and use of an off-the-shelf simulation package. Simulation is easier to implement and solve, but it does no yield an optimal solution; the user has to use a progressive user-driven search to improve the solution.
3. Development of an optimization model based on a more powerful optimization package, such as a Search Technique, for example GA, which is coded using a professional programming language such as VB or MATLAB.

Because of the many advantages and the transparency which is gained by the third option, we have developed our own mathematical models which were coded using the MATLAB programming language. However, to facilitate the use of our models for non-programmers end-users we have built an Excel-based interface for inputting the models' data and outputting the models' results (See Appendix 1).

3.1. DSS for Optimal Treatment Train Design

In this Section we present the development of a DSS for selecting the optimal treatment processes (i.e. different treatment technologies) which are to be included in a treatment train of an effluent stream which has a given stream size, inflow quality and required quality standard of the treated effluent. The kernel of this DSS is an optimization model that supports decision-making, embedded in a computer system that accepts data from a knowledge database of different treatment technologies and uses this data in an optimization model whose output are the decisions that reduce the overall cost of treatment and reuse. That is, the optimization model selects the treatment train that is optimal with respect to the sum of capital expenditures for constructing the treatment system, the Operational and Maintenance (O&M) expenditures, damage functions for crop production (when effluent quality is low), and costs of undesirable environmental consequence that may result from low quality effluent.

Beside the cost data, formulating the optimization models requires information on the other components of the system, specifically the options for decisions that can be made (feasible solutions). A "solution" is a treatment train of technologies which must meet physical and technological constraints. As such, the optimization model needs to account for cases where technology B cannot succeed technology A or cases where technology A must precede technology B.

3.1.1. Knowledge Database

An optimization model for the design of a wastewater treatment train requires a knowledge database that covers the set of technologies which are used in Israel and throughout the world. The knowledge database in this study was built based on the literature review (mainly from Huang et al. 2013, Brand and Ostfeld, 2011, Joksimovic, 2006, and Oron, 1996) as well as on interviews that we performed with different Israeli researches specialized in different aspects of wastewater treatment systems. Nevertheless, we aimed at making the knowledge database generic so it would be transportable to other locations and problems that deal with treatment of wastewater and reuse.

A series of four interviews were conducted with four Israeli researchers (See Appendix 2 for the questionnaires). We interviewed:

1. Professor Carlos Dosoretz, Faculty of Civil and Environmental Engineering, Technion, to gain insight and information on treatment technology, specifically on tertiary technologies such as Ultra Filtration (UF) and Reverse Osmosis (RO).
2. Professor Avi Shaviv, Faculty of Civil and Environmental Engineering, Technion, to gain insight and information on the effect of using effluents with different qualities on plants and soil.
3. Mr. Asher Eizenkot, Senior Advisor and Instructor on irrigation in the Ministry of Agriculture, to gain insight and information of the use of effluents for irrigation.
4. Dr. Jorge Tarchitsky, Faculty of Agriculture, Food and Environment, Hebrew University, former Scientist and Advisor at the Ministry of Agriculture, to gain insight and information on the effect of using effluents on plant, crop, soil and the environment.

The knowledge database considered in this study covers 44 treatment technologies in five categories (Table 3.1): 1) Preliminary treatment; 2) Primary treatment; 3) Secondary treatment; 4) Tertiary treatment; 5) Disinfection.

Table 3.1: Candidate Technologies

Category	Technology sub-ID*	Technology Name
Preliminary	1	None (**)
	2	Bar Screen
	3	Grit Chamber
	4	Coarse Screen
Primary	1	None
	2	Fine Screen
	3	Sedimentation w/o Coagulant
	4	Sedimentation w/ Coagulant
	5	DAF w/ Coagulant
	6	Membrane Filtration
	7	Actiflo®
	8	Stabilization Pond : Anaerobic
Secondary	1	None
	2	High Loaded Activated Sludge + Sec. Sedim.
	3	Low Loaded Activated Sludge w/o de-N + Sec. Sedim.
	4	Low Loaded Activated Sludge w/ de-N + Sec. Sedim.

	5	Trickling Filter + Secondary Sedimentation
	6	Rotating Biological Contactor
	7	Submerged Aerated Filter
	8	Stabilization Pond : Aerobic
	9	Stabilization Pond : Aerated
	10	Stabilization Pond : Facultative
	11	Constructed wetland: Free-Water-Surface Flow
	12	Constructed wetland: Subsurface Water Flow
	13	Membrane bioreactor
	14	Excess Biological Phosphorus Removal
	15	Phosphorus Precipitation
Tertiary	1	None
	2	Filtration over fine porous media
	3	Surface filtration
	4	Micro filtration
	5	Ultra-filtration
	6	Nano filtration
	7	Reverse osmosis
	8	Granular Activated Carbon
	9	Powdered Activated Carbon
	10	Ion exchange
	11	Advanced oxidation – UV/O3
	12	Advanced oxidation – UV/H2O2
	13	Soil Aquifer Treatment
	14	Maturation pond
	15	Constructed wetland - polishing
	16	Flocculation
Disinfection	1	None
	2	Ozone
	3	Paracetic acid
	4	Chlorine dioxide
	5	Chlorine gas
	6	Ultraviolet radiation

(*) Sub-ID refers to the order of the technology within a category.

(**) "None" is included to allow skipping this Category, i.e., not including it in the optimal solution.

The knowledge database considers ten water quality parameters: (1) Turbidity (Turb, NTU), (2) Total Suspended Solids (TSS, mg/L), (3) Biochemical Oxygen Demand (BOD, mg/L), (4) Chemical Oxygen Demand (COD, mg/L), (5) Total Nitrogen (TN, mg/L), (6) Total Phosphorus (TP, mg/L), (7) Fecal Coliforms (FC, #/100 ML), (8) Intestinal Nematode Eggs (INEggs, #/100 ML), 9) Escherichia Coli (Ecoli, #/100 ML), and 10) Salinity (mg/L).

For each of the 44 technologies the database includes ten expressions that quantify the performance (reduction in concentration) of the technology on each of the ten water quality parameters. Figure 3.1 shows an example of the functional relationships coded in the database. Figure 3.1 presents the removal efficiency for the third water quality parameter (i.e. BOD), under 16 different technologies. For example, the second row means technology 2 (i.e. Bar Screen) has a removal of 2.5% for BOD.

Note that our knowledge database includes the salinity as a water quality parameter, since it is an important parameter for irrigation with effluents in the Middle-East. The salinity concentration is not changed by conventional technologies, so the inclusion of salinity standard will induce advanced treatment technologies for salts removal such as NF membranes and RO.

```
fun_CellQ{3}{1}=@(C)C*(1-(0/100));
fun_CellQ{3}{2}=@(C)C*(1-(2.5/100));
fun_CellQ{3}{3}=@(C)C*(1-(4/100));
fun_CellQ{3}{4}=@(C)C*(1-(0/100));
fun_CellQ{3}{5}=@(C)C*(1-(2.5/100));
fun_CellQ{3}{6}=@(C)C*(1-(25/100));
fun_CellQ{3}{7}=@(C)C*(1-(50/100));
fun_CellQ{3}{8}=@(C)C*(1-(50/100));
fun_CellQ{3}{9}=@(C)C*(1-(82.5/100));
fun_CellQ{3}{10}=@(C)C*(1-(65/100));
fun_CellQ{3}{11}=@(C)2*Temp+20/100;
fun_CellQ{3}{12}=@(C)C*(1-(10/100));
fun_CellQ{3}{13}=@(C)C*(1-(7/100));
fun_CellQ{3}{14}=@(C)C*(1-(5/100));
fun_CellQ{3}{15}=@(C)C*(1-(60/100));
fun_CellQ{3}{16}=@(C)C*(1-(20/100));
```

Figure 3.1 - The quality equations defined as Matlab *handles* functions, (see User Manual in Appendix 1)

In addition to the performance of the unit processes, expressions for computing the annual capital and O&M costs of each unit process are included in the database of the model as shown in Table 3.2. Note that the capital and O&M cost in the knowledge database are given as functions similar to the performance functions in Figure 3.1. The values of the capital and the O&M costs in Table 3.2 are for fixed system configuration with the data given in Table 3.3. As can be seen from Table 3.3, systems parameters like average sewage inflow determine the capital and the O&M costs. In fact, all the costs are functions of the parameters in the first column of Table 3.3. The predetermined parameters of average flow, Q_{avg} , peak daily flow, Q_{pday} , dry weather flow, Q_{dwf} , serviced area population equivalents, PE, process area, A, and annually processed volume, V_{ann}, determine the capital and O&M costs. For example, for "Grit Chamber" technology, the capital cost is described by Equation (3.1) and the O&M cost is described by Equation (3.2).

$$C_{capital} = 20320 \cdot Q_{pday}^{(0.4426)} \qquad (3.1)$$

$$C_{O\&M} = 0.1 \cdot \mathrm{C}_{capital} \qquad (3.2)$$

where, Q_{pday} is peak daily flow (m^3 / hr) , $C_{capital}$ is capital cost ($) and $C_{O\&M}$ is operation and maintenance cost ($).

Table 3.2: The Capital Cost and O&M cost for all technologies (Source: Joksimovic, 2006)

Technology ID	Technology name	Capital Cost ($)	O&M Cost ($/year)
1	None	0.00	0.00
2	Bar Screen	373,875.26	33,828.38
3	Grit Chamber	422,536.44	42,253.64
4	Coarse Screen	598,674.75	59,867.47
5	Fine Screen	1,130,727.36	56,536.37
6	Sedimentation w/o Coagulant	1,522,683.92	30,453.68
7	Sedimentation w/ Coagulant	1,786,259.09	152,301.82
8	DAF w/ Coagulant	621,739.50	23,219.30
9	Membrane Filtration	4,749,728.38	606,876.49
10	Actiflo	4,593,298.09	303,964.89
11	Stabilization Pond: Anaerobic	720,553.34	49,181.38
12	High Loaded Activated Sludge + Sec. Sedim	3,204,582.87	307,069.40
13	Low Loaded Activated Sludge w/o de-N+Sec. Sedim	3,931,355.26	393,135.53
14	Low Loaded Activated Sludge w/ de-N+Sec. Sedim	4,133,850.86	413,385.09
15	Trickling Filter + Secondary Sedimentation	3,621,916.76	263,493.27
16	Rotating Biological Contactor	3,314,275.54	564,452.32
17	Submerged Aerated Filter	7,368,699.56	564,452.32
18	Stabilization Pond: Aerobic	1,269,742.19	49,181.38
19	Stabilization Pond: Aerated	316,977.83	49,181.38
20	Stabilization Pond: Facultative	1,591,514.86	49,181.38
21	Constructed wetland: Free-Water-Surface Flow	266,949.83	102,602.39

22	Constructed wetland: Subsurface Water Flow	29,920.00	102,602.39
23	Membrane bioreactor	6,667,503.70	0.19
24	Excess Biological Phosphorus Removal	148,360.09	8,891.60
25	Phosphorus Precipitation	38,744.81	18,200.00
26	Filtration over fine porous media	311,069.46	31,980.83
27	Surface filtration	475,030.73	71,254.61
28	Micro filtration	1,187,432.09	11,200.00
29	Ultra filtration	1,187,432.09	11,200.00
30	Nano filtration	1,966,531.66	15,400.00
31	Reverse osmosis	1,966,531.66	14,560.00
32	Granular Activated Carbon	2,126,618.59	376,216.10
33	Powdered Activated Carbon	4,895.03	21,000.00
34	Ion exchange	1,066,000.00	110,240.00
35	Advanced oxidation -UV/O3	505,189.34	21,000.00
36	Advanced oxidation -UV/H2O2	505,189.34	21,000.00
37	Soil Aquifer Treatment	7,840.00	17,500.00
38	Maturation pond	352,625.96	34,039.15
39	Constructed wetland - polishing	58,000,000.00	25,000,000.00
40	Flocculation	58,219.15	4,152.29
41	Ozone	1,721,631.30	131,231.97
42	Paracetic acid	1,225,324.20	42,000.00
43	Chlorine dioxide	1,225,324.20	107,647.23
44	Chlorine gas	1,225,324.20	154,847.23
45	Ultraviolet radiation	479,638.61	25,200.00

Table 3.3: System Configuration which is used to calculate the costs in Table 3.2

Parameter	**Description**	**Value**
Qavg (m^3/day)	Average flow	9,500
Qpday (m^3/hr)	Peak daily flow	950
Qdwf (m^3/day)	Dry weather flow	8,075
PE	Serviced area population equivalents	26,000
A (hectare)	Process area	1,000
Vann (m^3/year)	Annually processed volume	140,000
r (%)	discount rate	0.06
n (years)	Life time	25

Beside the cost data, formulating the optimization model requires information on the other components of the system, specifically the technological options which are feasible in the treatment train. As such, our knowledge database includes a set of rules that preclude certain combinations of processes in the treatment train or enforce a certain sequence. These rules are necessary to ascertain formation of treatment trains that are generally accepted in engineering practice and/or to impose specific preferences by the designer for combinations of treatment processes. The rules are inserted into the knowledge database to identify feasible and practical treatment trains that meet all assembly rules specified by the user. These rules are shown in Table 3.4. In each column the 1's represent the technologies which can come after the technology corresponding to this column. For example, the 1 in the second column and the fourth row indicates that Coarse Screening may come after Bar Screening. The 1's in the rows of Table 3.4 correspond to technologies that can precede the technology of corresponding row. For example, the second row (i.e. Bar Screening), has a single entry 1 in the first column (i.e. None) indicates that Bar Screening must be at the beginning of the treatment train. The 0's in the rows of Table 3.4 correspond to technologies that cannot precede the technology of corresponding row. For example, the fifth row (i.e. Fine Screen), cannot start the treatment train or precede the three first technologies.

Table 3.4: The Assembly Rules

	none	BScr	GrCh	CScr	FScr	Sed	SedC	DAF	DMF	Acti	SPAnbc	HLAs	LLAs	LLAsN	TF	RBC	SAF	SPAbc	SPAer	SPFac	WetFWS	WetSUB	MBR	EBPR	Ppre	MedF	SurF	MF	UF	NF	RO	GAC	PAC	IE	AOO3	AOH2O2	SAT	MP	WetPOL	Floc	O3	PA	ClO2	ClG	UV
none	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
BScr	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GrCh	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CScr	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FScr	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sed	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SedC	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DAF	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DMF	0	0	0	0	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Acti	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SPAnbc	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HLAs	1	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LLAs	1	0	0	0	0	1	1	1	0	1	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LLAsN	1	0	0	0	0	1	1	1	0	1	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TF	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RBC	0	0	0	0	0	1	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SAF	0	0	0	0	0	1	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SPAbc	0	0	0	0	0	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SPAer	0	0	0	0	0	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SPFac	1	0	0	0	0	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WetFWS	0	0	0	0	0	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WetSUB	0	0	0	0	0	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MBR	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EBPR	0	0	0	0	0	1	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ppre	0	0	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MedF	0	0	0	0	0	0	0	1	0	1	0	1	1	1	1	1	1	0	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
SurF	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0
MF	0	0	0	0	0	0	0	1	0	1	0	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	0	0	0	1	1	1	1	0	0	0	0	0
UF	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	0	0	0	1	1	1	1	0	0	0	0	0
NF	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0
RO	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
GAC	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1	0	0	0	0	0	1	1	0	1	1	1	1	0	0	0	1	1	1	0	0	1	0	0	1	0	0	0	0
PAC	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
IE	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AOO3	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AOH2O2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SAT	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	1	0	0	1	1	0	0	1	0	0	0	0	0	0
MP	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WetPOL	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Floc	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O3	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1	0	0	0	0	0	0	1	0	1	1	0	0	0	0	1	1	0	0	0	1	1	0	0	0	0	0	0	0
PA	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1	0	0	0	0	0	1	1	0	1	1	1	0	0	0	1	1	0	0	0	1	1	0	0	0	0	0	0	1
ClO2	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	1
ClG	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	1
UV	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1	0	0	0	0	0	0	1	0	1	1	0	0	0	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0

3.1.2. Conceptual Model

In this Section we formulate a conceptual optimization model which covers wastewater treatment technology and wastewater reuse. The conceptual optimization model identifies: possible objective functions to be optimized, decision variables, data needs, and constraints on the physical, chemical, biological and operational processes.

3.1.2.1. Objective Function

The objective function is total cost minimization: capital and O&M costs of building a treatment train. Other costs, such as economic losses and/or environmental problems which may arise because of using low quality water, can be incorporated in the model by using effluent dependent damage functions.

3.1.2.2. Constraints

Physical, technological and operational constraints for the selection of the treatment train are incorporated within the knowledge database by the assembly rules matrix in Table 3.4. Other physical constraints for the treatment process are given as quality constraints by the performance and the cost functions which are given in the knowledge database (Figure 3.1). More operation constraints are also imposed on the effluent quality, that is, the effluent quality must be below predetermined standards.

3.1.2.3. Decision Variables

The main decision is selection of a subset of technologies from a “bank” of given treatment technologies. Mathematically, the selection decision could be represented in various ways; each gives a different definition for the decision variables. Section 3.1.3 presents two formulations, one uses binary variables which take values 0-1 and the other uses integer variables in the range of the technologies' ID.

Beside the selection decision, there is a need for variables to define the ten water quality parameters considered in the problem. That is, for each selected technology 20 variables are needed to represent the water quality before and after the treatment technology is used.

While the quality variables themselves could be considered as decision variables in the problem, it is possible to extract them from the optimization problem if equality constraints are utilized.

That is, we can define the quality variables as dependent variables. As such, we define two types of variables:

1. Independent variables – Their values will be determined by the optimization (search) algorithm. The user provides an initial (guessed) value as input; it is modified iteratively by the algorithm in the direction of improving the value of the overall objective function.
2. Dependent variables – The values that are a function of the independent variables, and thus the optimization solver does not deal explicitly with their value; this reduces the search space for the optimization problem.

Following this conceptual model, we formulated two different optimization models for the problem: 1) Five-Stages Model; 2) Unlimited Stages Model.

3.1.3. Five-Stages Model

In this Section we developed and tested an optimization model that selects the treatment processes which are to be included in a treatment train of five stages (components) of an effluent stream which has a given stream size, inflow quality parameters and the required maximum levels of these parameters in the effluent from the system.

These five stages of the treatment train correspond to the five categories of technologies which are given in Table 3.1. That is, the problem is to select one technology from each of the five categories: 1) Preliminary treatment; 2) Primary treatment; 3) Secondary treatment; 4) Tertiary treatment; 5) Disinfection. The optimization model selects these five technologies to construct a train of length five that is optimal with respect to the total capital, O&M and damage costs. Selecting the technologies is done in specific order in which stage 1 is for preliminary, stage 2 is for Primary, and so on. The technologies selection is also under assembly rules constraints as detailed in the knowledge database (Table 3.4).

3.1.3.1. Formulation using binary variables

Mathematically, the technologies selection problem could be formulated in various ways. Here we consider the formulation using binary variables y_j, $j = 1...44$, one variable for each of the technologies in the knowledge database which represents whether the technology is inside the train ($y_j = 1$) or not ($y_j = 0$). Equation (3.3) presents the optimization problem with binary variables. In Equation (3.3), the first constraint defines the total cost, the second defines the capital cost and the third constraint defines the O&M costs. Since the variables y_j are binary, these constraints guarantee that only the costs of the selected technology are added.

The fourth constraint states that only one technology from each category can be selected and the fifth constraint represents the assembly rules as defined in Table 3.4. The sixth constraint defines the selected technology ID for each stage. The seventh constraint defines the outgoing water quality for the selected technology in each stage. The eighth constraint defines the water quality standards while the last constraint limits the variables to be binary.

$$\begin{aligned}
&Min\ TC \\
&\text{Subject to} \\
&TC = CC^{Capital} + CC^{O\&M} \\
&CC^{Capital} = \sum_{j=1}^{NT} y_j \cdot CC_j^{Capital} \\
&CC^{O\&M} = \sum_{j=1}^{NT} y_j \cdot CC_j^{O\&M} \\
&G(y_{\forall j}) = 0 \\
&F(y_{\forall j}) = 0 \\
&T_s = g_s(y_{\forall j}) && \forall s = 1,...,NS \\
&WQ_s^k = f_{T_s}\left(WQ_{s-1}^k\right) && \forall k = 1,...,10 \ \ \forall s = 1,...,NS \\
&WQ_{NS}^k \geq WQ_{\max}^k && \forall k = 1,...,10 \\
&y_j = \{0,1\} && \forall j = 1,...,NT
\end{aligned} \tag{3.3}$$

where, TC is total cost, $CC^{capital}$ is capital cost, $CC^{O\&M}$ is operation and maintenance cost, NT is number of technologies, y_j binary variable presenting a selected technology, NS is number of stage, $G(y_{\forall j})$ represent a constraint for one selected technology for each stage, $F(y_{\forall j})$ represent the assembly rules constraints, T_s are the selected technology for each stage (*s*), WQ_s^k is water quality for stage *k* and technology *s*, f_{T_s} is the performance function of technology T_s.

3.1.3.2. Formulation using integer variables

As can be seen in the previous formulation the binary variables formulation has a large search space of 2^{44} while a large portion of this domain is infeasible according to the constraint $G(y_{\forall j})=0$ which limits the number of technologies in each stage to one. It is possible to formulate a more efficient mathematical formulation by only exploring practically feasible options in the optimization domain rather than exploring the entire search domain, which consists of 2^{44} options. The new formulation utilizes Lagrange coefficients, an idea that we adapted from the field of discrete mathematics, to significantly reduce the search space of the model. The new formulation can reduce the computation time form $O(2^{NT})$ to $O(NT^5)$ where, NT is the number of technologies.

Equation (3.4) presents the optimization model based of this new formulation. The decision variables in this model are the integer variables T_s, $\forall s = 1...5$ for each of the five stages in the train. Each integer variable range is defined by the available technology for the corresponding stage as defined in Table 3.1. For example, the range of T_1 which correspond to the preliminary stage is four, since there are four available technologies for this stage as shown in Table 3.1. The product terms in the second and the third constraints are Lagrange coefficients which guarantee that only the costs of the selected technology are added. Note that unlike the binary formulation, the constraint $T_s = g_s(y_{\forall j})$ is not required in the new formulation, since the variables T_s are the independent decision variables of the optimization problem as shown in Equation (3.4).

$Min\ \ TC$

Subject to

$$TC = CC^{Capital} + CC^{O\&M}$$

$$CC^{Capital} = \sum_{s=1}^{NS}\sum_{j=1}^{NT_s}\left(\frac{\prod_{\substack{i=1\\ i\neq j}}^{NT_s}(T_s - i)}{\prod_{\substack{i=1\\ i\neq j}}^{NT_s}(j-i)}\cdot \mathrm{C}_{s,j}^{Capital}\right)$$

$$CC^{O\&M} = \sum_{s=1}^{NS}\sum_{j=1}^{NT_s}\left(\frac{\prod_{\substack{i=1\\ i\neq j}}^{NT_s}(T_s - i)}{\prod_{\substack{i=1\\ i\neq j}}^{NT_s}(j-i)}\cdot \mathrm{C}_{s,j}^{O\&M}\right) \qquad (3.4)$$

$$F(T_{\forall s}) = 0$$

$$WQ_s^k = f_{T_s}\left(WQ_{s-1}^k\right) \qquad \forall k = 1,\ldots,10 \quad \forall s = 1,\ldots, NS$$

$$WQ_{NS}^k \geq WQ_{\max}^k \qquad \forall k = 1,\ldots,10$$

$$T_s \in \{1, 2,\ldots, NT_s\} \qquad \forall s = 1,\ldots, NS$$

where, NT_s is the number of technologies available at stage s, $F(T_{\forall s})$ represents the assembly rules constraints.

3.1.3.3. Illustrative example for the integer formulation

For demonstration purposes let us consider the integer variables based formulation in Equation (3.4) for a two-stage treatment train as shown in Figure 3.2. Assume we have two stages of treatment: Preliminary and Primary treatment, where at each stage there are two candidate technologies:

1. Preliminary: (a) Bar Screen, or (b) Grit Chamber
2. Primary: (a) Fine Screen, or (b) Sedimentation w/o Coagulant

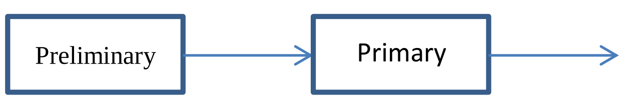


Figure 3.2 - Example of two stage treatment train

For the sake of this example let us assume that we only consider optimization of the capital cost. The optimization model for selecting the technologies for the two stages is given in Equation (3.5).

$$
\begin{aligned}
&Min\ \ CC \\
&\text{Subject to} \\
&CC = CC_{prel} + CC_{prim} \\
&CC_{prel} = \frac{(T_{prel}-2)}{(1-2)} CC_{prel,1} + \frac{(T_{prel}-1)}{(2-1)} CC_{prel,2} \\
&CC_{prim} = \frac{(T_{prim}-2)}{(1-2)} CC_{prim,1} + \frac{(T_{prim}-1)}{(2-1)} CC_{prim,2}
\end{aligned}
\tag{3.5}
$$

Where, T_{prel} is a binary technology selection coefficient with values {1,2} for the preliminary stage; $CC_{prel,1}$ is capital cost of technology 1 in preliminary stage; $CC_{prel,2}$ is capital cost of technology 2 in preliminary stage; T_{prim} is a binary selection coefficient with values {1,2} for the primary stage; $CC_{prim,1}$ is capital cost of technology 1 in primary stage; $CC_{prim,2}$ is capital cost of technology 2 in primary stage.

The costs functions for these technologies as listed in the knowledge database are given in Table 3.5. These capital costs are obtained from Appendix A in Joksimović (2006).

Table 3.5: Relationships for capital cost

Category	ID	Technology	Capital Cost ($)
Preliminary	1	Bar Screen	$11035Q_{peak}^{0.5138}$
	2	Grit Chamber	$20320Q_{peak}^{0.4426}$
Primary	1	Fine Screen	$42280Q_{peak}^{0.4793}$
	2	Sedimentation w/o Coagulant	$13667Q_{avg}^{0.5146}$

If we consider a problem with $Q_{peak} = 400(m^3/hr)$ and $Q_{avg} = 4000(m^3/day)$, we obtain numerical values for the capital cost of each technology for each stage as shown in Table 3.6. Using these numerical values of the capital costs we obtain the optimization model in Equation (3.6).

$$
\begin{aligned}
&Min\ \ CC\\
&\text{Subject to}\\
&CC = CC_{prel} + CC_{prim}\\
&CC_{prel} = \frac{(T_{prel}-2)}{(1-2)}239723 + \frac{(T_{prel}-1)}{(2-1)}288134\\
&CC_{prim} = \frac{(T_{prim}-2)}{(1-2)}746968 + \frac{(T_{prim}-1)}{(2-1)}1522683\\
&T_{prel} \in \{1,2\}\\
&T_{prim} \in \{1,2\}
\end{aligned}
\tag{3.6}
$$

where, T_{prel} and T_{prim} are integer variables that determine the selection between the alternative technologies for each stage, and thus fix the configuration of the treatment train. In this example, the problem results in four feasible configurations [1, 1], [1, 2], [2, 1] and [2, 2], and the optimal one (i.e. the least cost) is selected according to the value of the objective function.

Table 3.6: Numerical values for the capital cost

Category	ID	Technology/ symbol	Capital Cost ($)
Preliminary	1	Bar Screen ($CC_{prel,1}$)	239,723
	2	Grit Chamber ($CC_{prel,2}$)	288,134
Primary	1	Fine Screen ($CC_{prim,1}$)	746,968
	2	Sedimentation ($CC_{prim,2}$)	1,522,683

3.1.4. Optimization Solver

To solve the optimization problem in Equation (3.4), we used Matlab's Genetic Algorithm (GA) solver for searching the decision domain. We used the GA solver without explicitly adding the constraints in the solver. Instead, we have added the constraints through a penalty function that converts the problem to an unconstrained optimization problem as shown in Equation (3.7).

$$
\min_{x}\left[\text{cost}(x) + \text{P}\cdot\max(\text{g}(x),0)\right] \tag{3.7}
$$

where x is the decision variables vector, g(x) is the left hand side of the constraints of the type $g(x) \le 0$ and P is a penalty factor.

The penalty function includes infeasibilities in the technology sequence in stages of the treatment train. For example, if technology B in stage 2 is not valid after technology A of stage 1, then the penalty factor, P, is set high enough when this combination is being considered, as compared to the real cost values, such that this technology combination is excluded.

GA is a black-box optimization solver, in the sense that it does not require any information regarding the mathematical properties of the problem. For the GA to communicate with the mathematical model, it only requires the definition of an evaluation function as shown in Figure 3.3. GA suggests different values for the decision vector while the evaluation function returns the scores (i.e. cost plus penalty) of these solutions. The GA uses operators such as crossover and mutations, based on the obtained scores, to create a "better" set of solutions for the problem. This search process continues until a convergence criterion is met or a maximum specified number of iterations are reached.

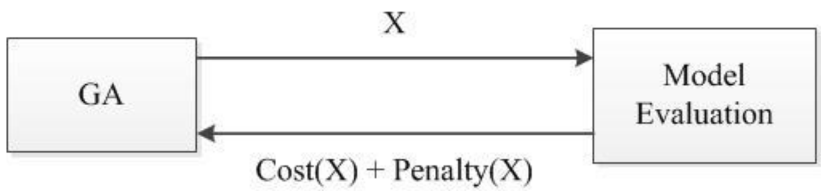


Figure 3.3 - GA search process

3.1.5. Testing the Five-Stages Model

Following the development of the knowledge database and the mathematical model in Equation (3.4), we tested the Five-Stages Model under various conditions to check its validity and to investigate its performance under different conditions. The first (trivial) experiment was to set all the effluent quality parameters required at the end of the treatment train to very high concentration values, in fact higher concentrations than the inflow levels. As expected, under this condition the model chose not to build the treatment train at all. This also yields the minimum total annual cost solution, i.e. zero, and results in untreated effluent.

3.1.5.1. Base Run

Next, we considered the design of a wastewater treatment plant with capacity of 9,500 (m^3/d) and influent quality as listed in the first row of Table 3.7. The problem parameters are given in Table 3.3 and the costs data is given in Table 3.2.

The reclaimed effluent at the end of the treatment train must meet the effluent quality levels listed in the last row of Table 3.7. The minimum cost solution under these conditions was determined by running the model and yielded the following optimal treatment train which is also listed as the first column in Table 3.7: 1) Bar Screen, 2) Dissolved Air Flotation (DAF) with Coagulant, 3) Stabilization Pond: Aerated, 4) Reverse Osmoses, 5) No disinfection process is selected in this optimal configuration.

Table 3.7 presents the water quality at the end of each stage in the treatment train. The influent wastewater data is approximated and assumed data that does not purport to represent an actual wastewater plant data. The influent and required effluent data will have to be stated by the user. For each water quality parameter, the bold number denotes the stage in which the required final effluent water quality level is already attained or exceeded. For example the Aerated Stabilization Pond already achieves the required quality of TSS, BOD and TN.

Table 3.7: Solution of the Base Run: influent secondary wastewater quality and output tertiary effluent quality after the selected technologies in each of the five stages

Selected Technology	**Turb (NTU)**	**TSS (mg/L)**	**BOD (mg/L)**	**COD (mg/L)**	**TN (mg/L)**	**TP (mg/L)**	**FC (#/100 ML)**	**INEggs (#/100 ML)**
Influent wastewater quality	225.0	155.0	133.0	600.0	19.0	4.0	1000000.0	800.0
Bar Screen	225.0	155.0	129.7	591.0	19.0	4.0	1000000.0	800.0
DAF w/ Coagulant	67.5	46.5	64.8	295.5	16.2	0.8	**316.2**	**0.1**
Stabilization Pond: Aerated	20.3	**9.0**	**8.1**	103.4	**8.5**	0.4	77.2	0.0
Reverse Osmoses	**8.1**	0.1	4.5	**10.3**	4.2	0.0	0.0	0.0
No Disinfection	8.1	0.1	4.5	10.3	4.2	0.0	0.0	0.0
Required effluent quality	10.0	10.0	10.0	70.0	10.0	0.2	10000.0	0.1

3.1.5.2. Sensitivity Analysis (SA)

The Effect of Plant Capacity

The first SA examines the change in the optimal treatment train and the optimal annual costs under different plant capacities, given water quality requirements in Table 3.7. Figure 3.4 presents the change in the treatment train as a function of plant capacity, for the range between 1,000 and 10,000 (m^3/day). The y-axis presents the sub-ID of the technology for each stage of the treatment plant as detailed in Table 3.1. For example we can see that for all capacities in this range, Bar Screen is selected in the preliminary phase (Technology ID=2 in preliminary stage, blue line).

Figure 3.4 shows that two treatment trains are optimal for the all capacities considered in the analysis. These two trains only differ in the tertiary treatment, beyond the 2000 (m^3/day) the selected technology is Microfiltration (ID=4) while below 2000 (m^3/day) the selected technology is Reverse Osmosis (ID=7).

Figure 3.5 presents the change in the annual capital and O&M costs as a function of the plant capacity. The results show that the total, the capital and the O&M costs are increasing with the capacity. The results also show that the O&M cost becomes more significant (as a portion of the capital cost) when large capacity is considered.

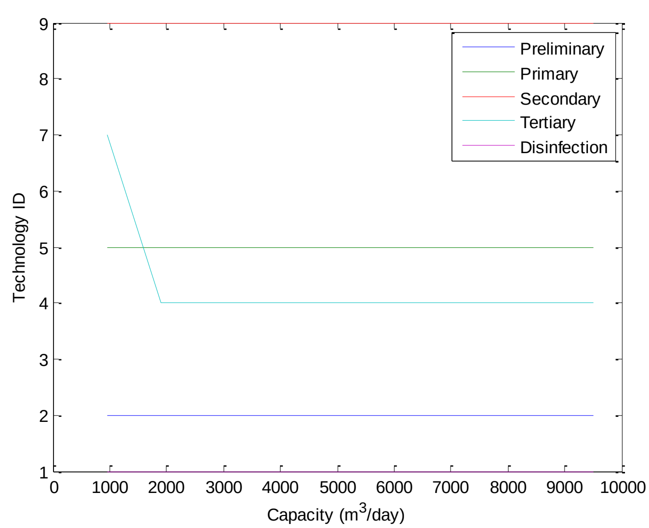


Figure 3.4 - Optimal treatment trains for different plant capacities

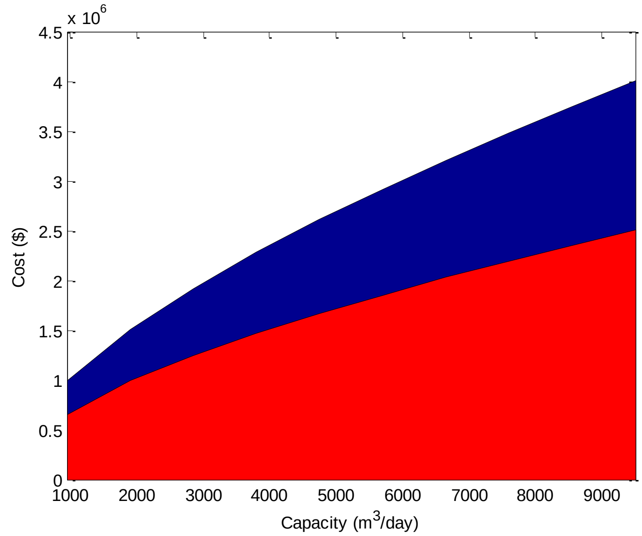


Figure 3.5 - Optimal annual cost of the treatment train as a function of plant capacity (Red = capital cost, Blue = O&M cost)

Sensitivity to Values of Various Quality Requirements in the Final Effluent

We next performed Sensitivity Analyses of the model performance for a plant capacity of 9,500 (m^3/day) under various requirements for final effluent quality, as listed in Table 3.8.

Table 3.8: Final effluent maximum quality standards for 4 SA runs

SA Run	Turb (NTU)	TSS (mg/L)	BOD (mg/L)	COD (mg/L)	TN (mg/L)	TP (mg/L)	FC (#/100 ML)	INEggs (#/100 ML)
1	50	50	50	50	50	50	10,000	50
2	50	50	50	50	50	50	10,000	50
3	10	10	10	70	10	4	10,000	0.1
4	10	10	100	70	10	0.2	10,000	0.1

Sensitivity Analysis 2 and 3 explore the change in the solution as a result of changing the BOD and the TP at the end of the treatment plant, respectively. Figure 3.6 presents the optimal treatment train obtained for different levels of BOD and Figure 3.7 shows the change in the capital and O&M costs. As shown in Figure 3.6, three different treatment trains are obtained for changing levels of BOD; these trains differ in the secondary and the tertiary stages. For example, when maximum allowed BOD level is 40 (mg/lit) the selected tertiary technology is 4 which corresponds to Micro Filtration according to Table 3.1, but when maximum allowed BOD level is 100 (mg/lit) then the selected tertiary technology is 14 which corresponds to Maturation pond treatment. Figure 3.7 shows that the total cost of the train is decreasing when the maximum allowed BOD increases. It is expected that the cost decreases when the water quality standards are lowered.

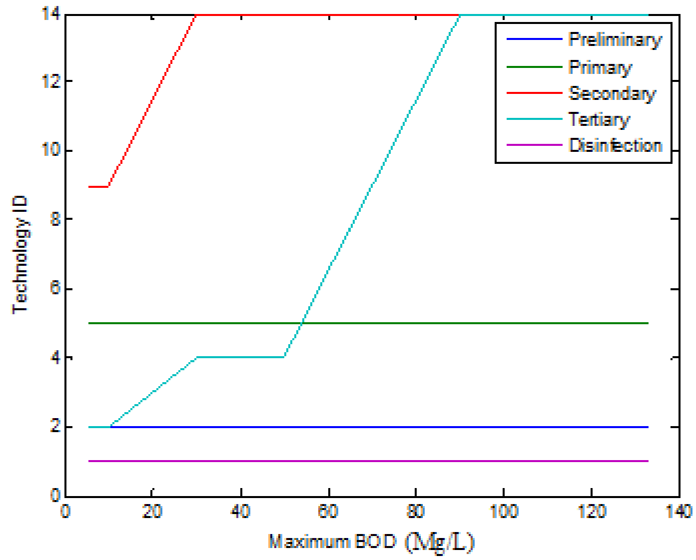


Figure 3.6 - Optimal treatment trains in Sensitivity Analysis 2: The effect of change in the required final BOD (mg/L)

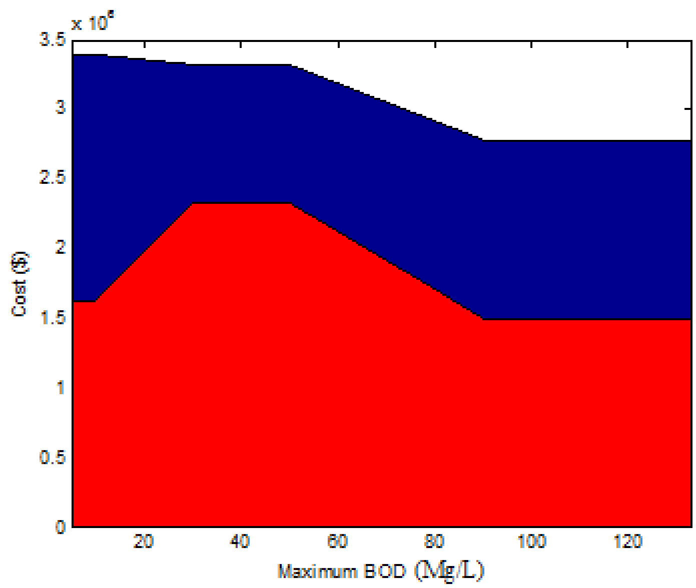


Figure 3.7 - Optimal capital (red) and O&M (blue) costs in Sensitivity Analysis 2

Similar to the previous analysis, Figure 3.8 and 3.9 present the optimal treatment train and the costs for different levels of TP, respectively. The results show that only two optimal treatment trains exist for changing TP, these two trains only differs by the tertiary treatment. The first is using Reverse Osmosis when TP values are below 0.2 mg per liter and the second is using Microfiltration when TP is higher than 0.2 mg per liter. Figure 3.9 shows that the total cost of the train is decreasing when the maximum allowed TP increases. That is when the water quality standards are lowered, the total cost of the train is decreased.

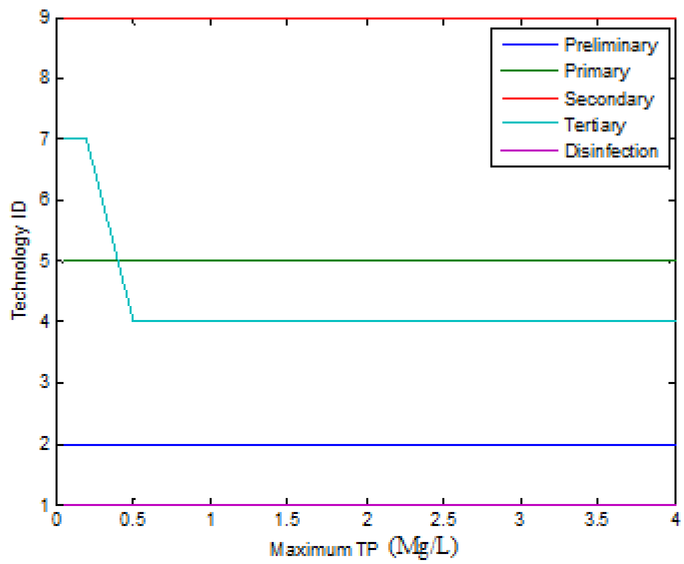


Figure 3.8 - Optimal treatment train in Sensitivity Analysis 3: The effect of change in the required final TP (mg/L)

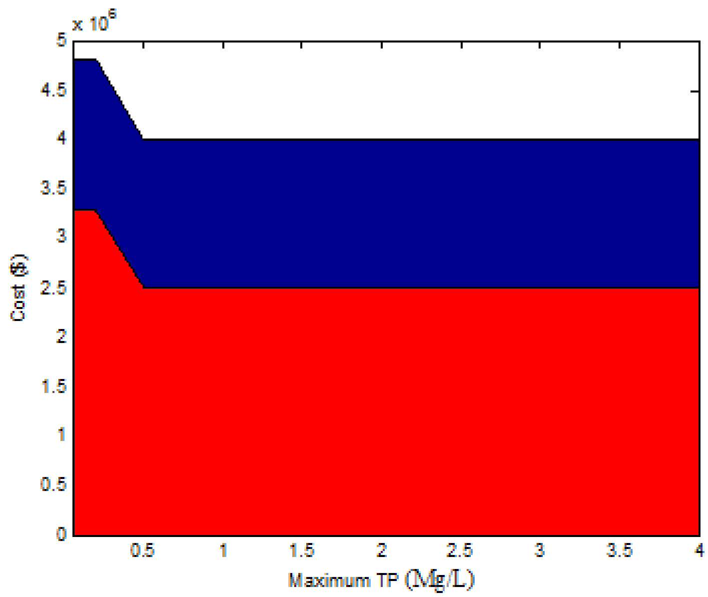


Figure 3.9 - Optimal annual capital (red) and O&M (blue) costs versus required TP (mg/L) of the final effluent.

Organic matter present in secondary effluents can cause membrane fouling during Reverse Osmosis in tertiary treatment. To prevent this, one can constrain the BOD in the secondary phase to a predetermined maximum level. Sensitivity Analysis 4 examines the impact of different BOD levels in the secondary effluent on the treatment train. Figure 3.10 shows the optimal treatment train when changing the BOD level of the incoming secondary effluent. The results show that the optimal treatment train is sensitive to the BOD level of the secondary effluent, especially when the BOD requirement is below 10 mg per liter; three different treatment trains where obtained within this range.

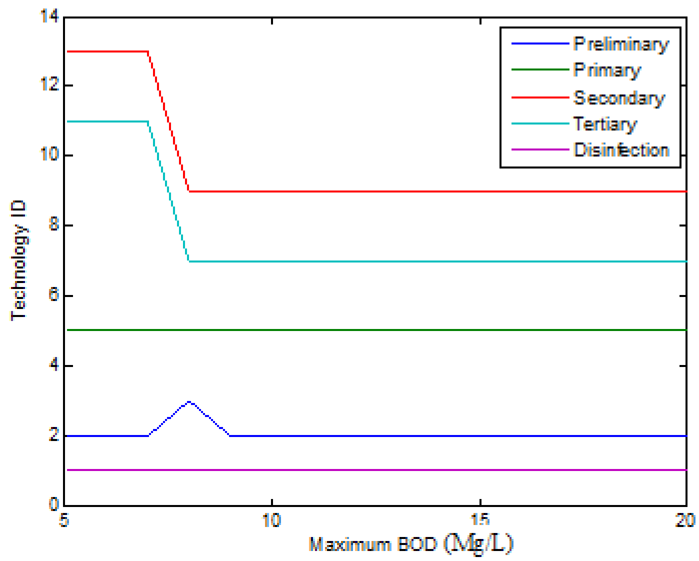


Figure 3.10 - Optimal treatment trains in Sensitivity Analysis 4.

3.1.6. Unlimited-Stages Model

In this Section we develop a treatment design optimization model with unlimited number of stages. Unlike the Five-Stages Model which consists of selecting an optimal technology for each of the five stages in the train: 1) Preliminary treatment; 2) Primary treatment; 3) Secondary treatment; 4) Tertiary treatment; 5) Disinfection, in this model we consider unlimited treatment train without an a-priori fixed number of stages. This change allows the model to choose any available technology consistent with the treatment train synthesis rules and thus facilitating a more generic representation of the treatment train combinations. Equation (3.8) presents the optimization model for the unlimited stage model. Compared to Equation (3.4) which present the Five-stages Model, in the new model we have the number of the stages, NS, as a decision variable. Moreover, the technologies decision variables, T_s, $\forall s = 1 \ldots NS$ are integer variables with the range of the entire technologies set (i.e. 44) as opposed to a range which is defined by the available technology for the corresponding stage in the Five-stages Model.

$$
\begin{aligned}
&Min\ \ TC \\
&\text{Subject to} \\
&TC = CC^{Capital} + CC^{O\&M} + DC \\
&CC^{Capital} = \sum_{s=1}^{NS}\sum_{j=1}^{NT}\left(\frac{\prod_{\substack{i=1\\ i\neq j}}^{NT}(T_s - i)}{\prod_{\substack{i=1\\ i\neq j}}^{NT_s}(j-i)}\cdot \mathrm{C}_{s,j}^{Capital}\right) \\
&CC^{O\&M} = \sum_{s=1}^{NS}\sum_{j=1}^{NT}\left(\frac{\prod_{\substack{i=1\\ i\neq j}}^{NT}(T_s - i)}{\prod_{\substack{i=1\\ i\neq j}}^{NT_s}(j-i)}\cdot \mathrm{C}_{s,j}^{O\&M}\right) \\
&F(T_{\forall s}) = 0 \\
&WQ_s^k = f_{T_s}\left(WQ_{s-1}^k\right) \qquad \forall k = 1...10 \ \ \forall s = 1...NS \\
&WQ_{NS}^k \geq WQ_{\max}^k \qquad \forall k = 1...10 \\
&DC = \sum_{k=1}^{10} DC^k (WQ_{NS}^k) \\
&T_s \in \{1, 2, ..., NT\} \qquad \forall s = 1...NS
\end{aligned}
\qquad (3.8)
$$

where DC is damage cost, DC^k is damage cost for quality parameter *k*.

A new feature of the unlimited stages model is that we added damage cost function to the other cost components of capital costs and O&M costs as can be seen in the second-to-last constraint of Equation (3.8). Damage cost is a function of the quality parameters, so we have ten damage functions. They represent the cost of damage to soil, water and the enrolment. Each function is defined as a piecewise linear function with three segments (four points), and indicates the damage cost when using effluents with specific quality. Figure 3.11 shows the damage cost for salinity. This damage function could be a representation of how the salinity affects the yield, for example. The x-axis is the salinity concentration, and the maximal concentration is the influent salinity concentration; the y-axis is the damage cost, measured as ($) or ($m^3$/day). The concentration of salinity does not affect the yield up to a certain level, and then the damage to the yield grows exponentially. Each quality parameter can have a different effect on the damage cost function, thus similar cost functions (as in Figure 3.11) have to be defined for each of the ten quality parameters in the system, and these functions are part of the knowledge database (see User Manual, Appendix 1).

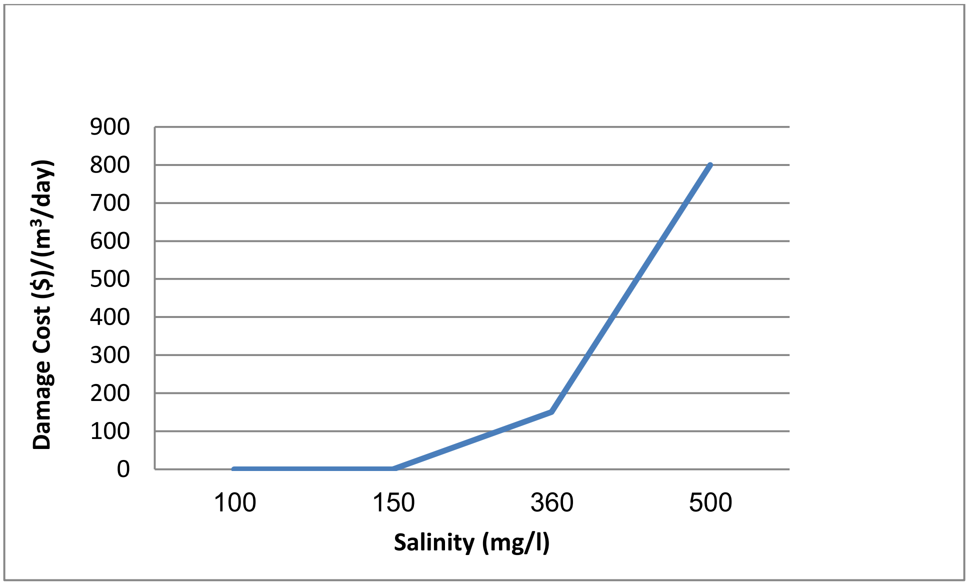


Figure 3.11 - The damage cost function as a function of salinity concentrations

3.1.7. Testing the Unlimited-Stages Model

The optimization is designed to select the technologies of the treatment train such that the overall cost of capital, present value of O&M, and damage costs of the entire treatment train is minimized. It uses a Genetic Algorithm (GA) by invoking this algorithm as explained in the User Manual, Appendix 1.

We tested the model under various conditions to check its validity and to investigate its performance under different conditions. The first experiment was to set all the required concentrations of the wastewater quality parameters at the end of the treatment train to very high level, in fact higher than the inflow level, which means that no treatment at all is required and the treatment train is merely a "flow through". As expected, under this condition the model chose not to build the treatment train at all. This also yields the minimum total cost of zero and results in effluent quality = influent quality for all quality parameters.

3.1.7.1. Base Run

Next, we considered the design of a wastewater treatment plant with capacity of 9,500 (m^3/d) and influent quality as listed in the first row of Table 3.9. The problem parameters are given in Table 3.3 and the costs data is given in Table 3.2.

The effluent at the end of the treatment train must meet the predetermined effluent quality levels listed on the last line of Table 3.9. The minimum cost solution under these conditions was determined by running the model, which yielded the following optimal treatment train, also listed in the first column of Table 3.9: 1) None, 2) Stabilization Pond: Anaerobic, 3) Phosphorus Precipitation, 4) Filtration over fine porous media, 5) Advanced oxidation UV/ H_2O_2, 6) Soil Aquifer Treatment, 7) Filtration over fine porous media, 8) Ultra-Filtration 9) Soil Aquifer Treatment, are selected in this optimal configuration. Table 3.9 presents the wastewater quality at the end of each stage in the treatment train. For each wastewater quality parameter, the bold number denotes the stage in which the required final effluent quality level is already attained or exceeded. In Figure 3.12 and 3.13, we can see how the GA optimization method is searching for the optimal solution. Figure 3.12 shows the search process in the infeasible region (points with high penalty as observed on the y-axis with value of magnitude 1e+20). Figure 3.13 shows the improvement of the objective function when starting the GA from a feasible solution.

Table 3.9: Solution of the Base Run: influent secondary wastewater quality and output tertiary effluent quality after the selected technologies in each of the 8 stages

	Selected Technology	**Turb (NTU)**	**TSS (mg/L)**	**BOD (mg/L)**	**COD (mg/L)**	**TN (mg/L)**	**TP (mg/L)**	**FC (#/100 ML)**	**INEggs (#/100 ML)**
	Influent wastewater quality	225.0	155.0	133.0	600.0	19.0	4.0	1000000.0	800.0
Stage	Effluent quality at the exit from each stage								
1	None	225.0	155.0	133.0	600.0	19.0	4.0	1000000.0	800.0
2	Stabilization Pond: Anaerobic	67.5	31.0	42.2	255.0	9.9	3.7	244259.9	90.4
3	Phosphorus Precipitation	67.5	31.0	42.2	255.0	9.9	3.7	244259.9	90.4
4	Filtration over fine porous media	14.2	**9.3**	25.3	159.4	9.9	2.4	61065.0	90.4
5	Advanced oxidation UV/ H_2O_2	**1.4**	9.3	**1.3**	**15.9**	9.9	2.4	**1526.6**	2.3
6	Soil Aquifer Treatment	0.07	0.05	0.04	2.2	**1.1**	**0.05**	0.05	2.3
7	Filtration over fine porous media	0.01	0.01	0.03	1.3	1.1	0.03	0.01	2.3
8	Ultra-Filtration	0.0	0.0	0.005	0.5	1.0	0.02	0.0	**0.0**
9	Soil Aquifer Treatment	0.0	0.0	0.0	0.08	0.1	0.0	0.0	0.0
	Required effluent quality	10.0	10.0	10.0	70.0	10.0	0.2	10000.0	0.1

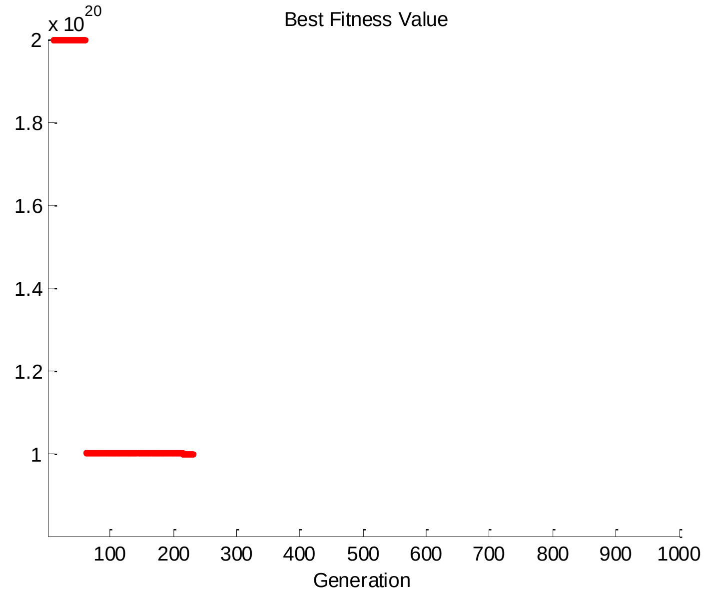


Figure 3.12 - Value of the objective function in the infeasible region during the search of GA optimization method

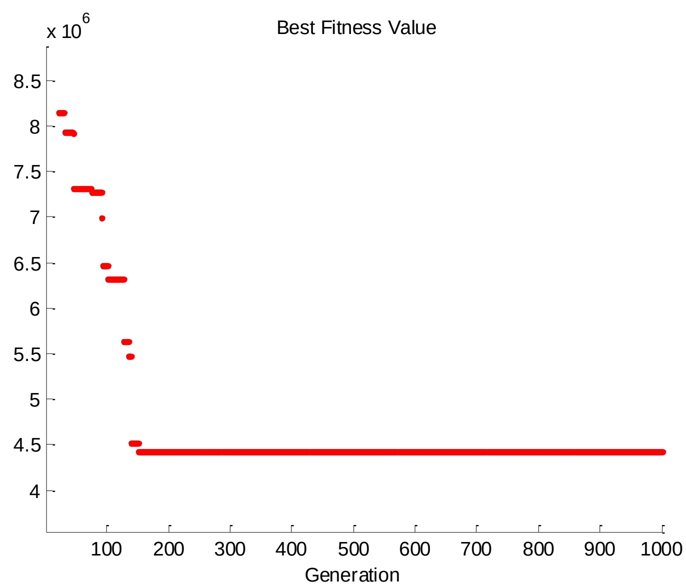


Figure 3.13 - Value of the objective function in the feasible region during the search of GA optimization method

3.1.7.2. Sensitivity Analysis (SA)

The Effect of various Damage Cost Functions

Here we examine how the damage cost function of the quality parameter, BOD, affects the optimal treatment train. We considered four different damage cost functions given in Figure 3.14 and Tables 3.10 and 3.11. In Figure 3.15, we can see how the optimal treatment train changes while we change the damage cost function of the BOD. For SA_D, we can see the decreasing BOD concentration among the treatment train technologies in Figure 3.16. Figure 3.16, shows that the major BOD reduction is obtained with the first technologies in the treatment train. For each of the ten quality parameters, we expect a reduction in the concentration. In Figure 3.14, we can see that the higher the concentration of BOD is the higher the damage cost.

Figure 3.15 shows that technology number 2 (i.e. High loaded Activated Sludge + Sec. Sedim) is chosen to be the same technology for all the runs despite the differences in the damage cost. The selected technology is known for its high efficiency in BOD removal. Selecting the rest of technologies is based on least O&M and capital costs, besides the damage cost. Yet, in Figure 3.15, we can see that the chosen treatment train technologies for SA_D is different from the other technologies chosen for the other SAs, after stage 2 none of scenarios resulted in the same technologies obtained in SA_D (unlike SA_B and SA_C which share a lot of technologies). We can see that most the technologies chosen for SA_D are based on filtration.

In Figure 3.16, we can see that within the technologies of SA_D, we can get almost zero concentration of BOD at the end of the treatment train technologies. This high BOD removal is obtained within the first five stages with the highest removal coming from the first stage technology (i.e. Bar Screen). This indicates that when this technology is available one should use it, to achieve lower soil damage that would result from high BOD concentration.

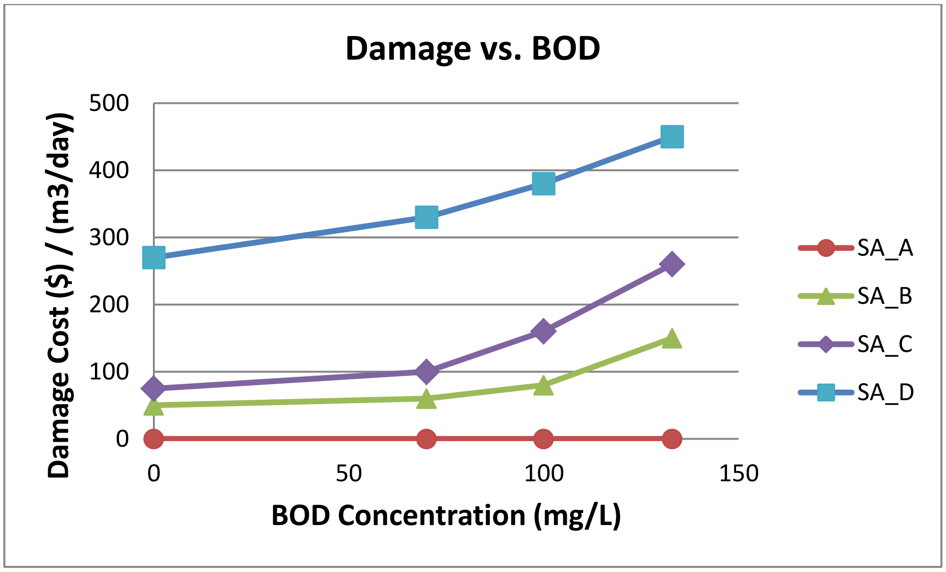


Figure 3.14 - Damage cost functions as function of BOD concentration

Table 3.10: The Data for damage cost functions as BOD concentration

Parameter Name	BOD (mg/L)
Point 1	0
Point 2	70
Point 3	100
Point 4	133

Table 3.11: Damage Cost Data for four different Sensitivity Analysis (SA) runs

Parameter Name / SA Run	SA_A	SA_B	SA_C	SA_D
Damage @ Point 1	0	50	75	270
Damage @ Point 2	0	60	100	330
Damage @ Point 3	0	80	160	380
Damage @ Point 4	0	150	260	450

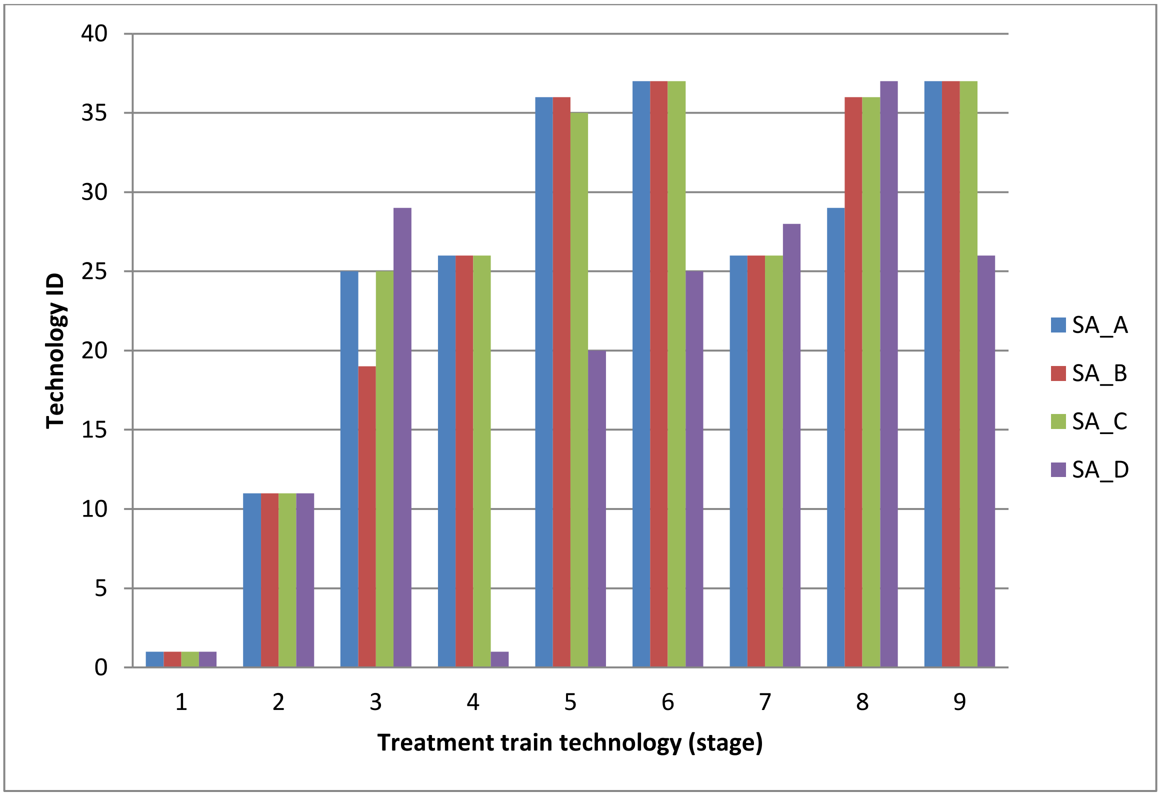


Figure 3.15 – Different optimal treatment trains obtained with four different damage functions

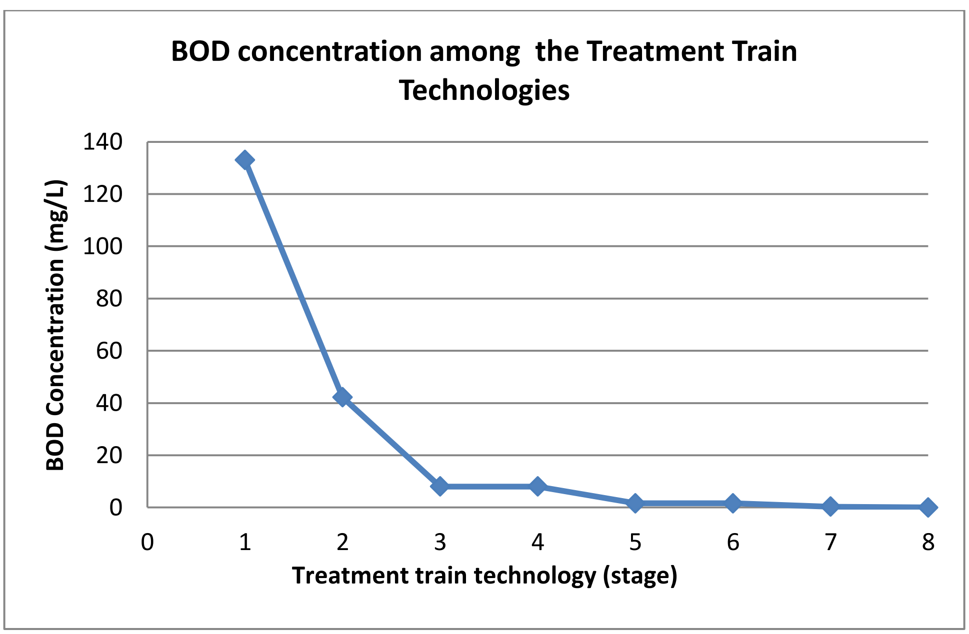


Figure 3.16 - BOD concentration along the Treatment Train Technologies for SA_D run

3.1.8. The DSS Program

The mathematical models developed in this work were coded using the MATLAB programming language. To facilitate the use of our models for non-programmers end-users we built an Excel-based interface for inputting the model data and outputting the results. The optimization model is a central component in the computer system that also includes ancillary programs for receiving and handling input data and for casting the results (the output) of the optimization in forms and formats that support decision-making. The following Appendices are part of this thesis:

1.1. "User's Manual: DSS for Optimal Treatment Design".
1.2. "DSS setup files.zip": Install files for running the optimization model.

3.2. Regional Planning Model of Wastewater Treatment System

The main focus of this work was to develop the treatment train optimal design DSS described is Section 3.1. As a secondary product of this thesis, and building on the treatment train optimization model, we have also developed a regional planning model of wastewater and effluent transport and storage system, as laid out in Figure 3.17. The layout shows all potential components of the system. "Potential" means that the optimization will select which of the facilities shown will be selected, with their sizes, while others will not appear in the optimal solution (their size will be zero).

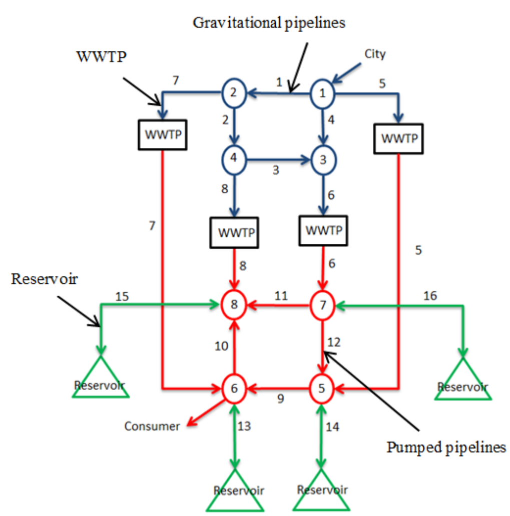


Figure 3.17 - The potential layout problem

The model consists of Waste Water Treatment Plants (WWTPs), gravitational pipes (in blue) that carry wastewater from the sources to WWTPs which treat the wastewater, pumped pipes carrying treated wastewater (effluents, in red) from the WWTPs, and reservoirs (in green) as presented in Figure 3.17. The system is to operate over three sequential seasons and the decision problem includes finding the optimal layout of the system, the optimal design (i.e. sizing of the different components) and the seasonal flows, such that the total capital and operation cost is minimized, subject to physical, technological and operational constraints.

3.2.1. Model Outline

The model is divided into two problems, the layout selection problem and the design problem. The layout selection problem is about finding which components, out of the potential components shown in Figure 3.17, should be present in the optimal solution. As such, one may think of the decision variables in the layout decision problem as binary variables indicating whether the component is "on" or "off".

The design problem is about finding the optimal sizing for the selected components in the layout problem and determining the sizing of the different components, which requires calculating the flows in the system over time. This is because the flow in the network is a function of the selected layout and sizing of its components. For example, to determine the reservoir size the flow in the system must be determined along time, and to determine the size of the pipes the maximum flow over the entire operation time must be determined. For this purpose the selected layout is considered in the three successive seasons to determine the operational flows if this layout is to be chosen. The representation of the operation in these three seasons is given in Figure 3.18, from left to right. The arrows outgoing from the reservoirs are the transitions of storage in the reservoirs at the end of one time period to make them the initial storage in the next time period. The arrows emerging from the reservoirs at t=3 are the final values at the end of the planning horizon. The representation in Figure 3.18 is defined as a "space-time" network of the system since it depicts both the flows in the different components (i.e. space) and the transition of storage between seasons (i.e. time).

In the system shown in Figure 3.18, there is one wastewater source (i.e. a city) which is at nodes 1, 9 and 17. These three nodes represent the same city but in different seasons. For example, node 9 receives the wastewater flow from the city to the network in season 2. Also, we consider one consumer of reclaimed water, which is located at nodes 8, 16 and 24 in the three seasons.

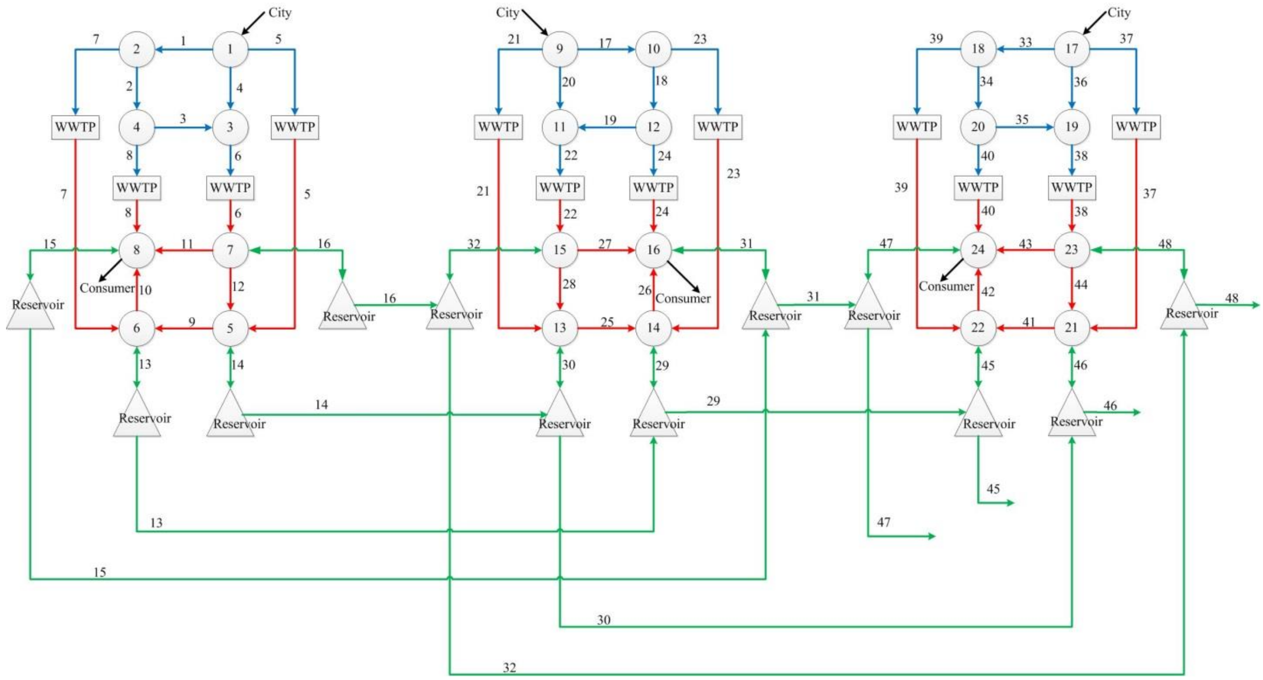


Figure 3.18 – The space-time network

Figure 3.18 has eight spatial nodes, nodes 1-4 represent predefined potential locations where a WWTP can be built, while nodes 5-8 represent predefined potential locations where reservoirs can be built. Wastewater sources could feed nodes 1-4 while consumers are supplied from nodes 5-8. In our example, for period 1, the wastewater comes from one city at node 4 and one consumer is located at node 8. In terms of the connectivity between the eight predefined locations, consider four potential gravitational pipes which convey wastewater; these pipes are represented by links 1-4. In Figure 3.18, blue links are for sewage and red are for effluent (after treatment) conveyors. Note that the inflow and outflow links of the WWTPs are given two colors, because they convert the sewage into reclaimed water.

In the layout problem the optimal solution will determine which of these pipes should be present in the optimal plan of the network. Wastewater flows through WWTP which are represented by four links 5-8. There are four WWTP's which are associated with the four nodes. That is, if a WWTP is to be built at node 1, then link 5 will be activated, indicating that this WWTP is to be built in the final layout and it will deliver effluent from node 1 to node 5.

As indicated earlier, nodes 5-8 are predefined location where reservoir could be built. These locations are connected with four potential pipes which convey effluents; these pipes are represented by links 9-12. Effluents can be stored from one season to the next; this is represented by considering four potential reservoirs which are represented by four links 13-16. For example, if a reservoir is to be built at node 7 then link 16 will be active in the layout optimal solution.

In Figure 3.18, wastewater and effluents can flow only in the direction of the arrows; that is a restriction over the decision on the direction of the flow in the layout problem. It is noteworthy that this restriction can be relaxed by considering two parallel links, with opposite directions, for each pipe in the system. The restriction of the direction done for two reasons: 1) to ease the demonstration of the example; 2) in real-life when the locations are predefined, it is often easy to determine what the flow direction in the pipe is.

The Decision Problem of Design and Operation

The decision problem is divided into two groups: the design/layout part and the operation part. The decision problem of the layout is about choosing the components which should be in the optimal solution such as pipes, WWTP and reservoirs. The design problem is about determining the optimal sizing of all components, considering the capital and the operation cost subject to constraints.

It is possible to distinguish between the layout and the design problems by considering binary decision variables which indicates whether the component is part of the solution or not. Herein, we follow a different approach in which considering the layout problem to be part of the design problem, by requiring the size of components to be greater than a very small value ("epsilon") in the design stage. That is, instead of having a [0,1] binary variable which indicates that the component is present in the optimal solution or not, we require a lower bound of “close-to-zero” as an option in the sizing problem. The small lower bound (but not zero) avoids numerical difficulties in running the optimization algorithm. If a component takes on this value in the solution this indicates that it is zero (i.e. eliminated) in the solution.

There are several advantages to merging the design and the layout problems, among them: 1) a substantial reduction in the size of the optimization problem; 2) there is no need to change the graph representation during the solution process, that is no links are deleted from the graph, all links always exist, but inactive ones have size zero. This second advantage facilitates a straightforward formulation and prevents numerical problems which may occur if the other approach is considered in which binary variables are considered to deactivate components.

Hence, after merging the layout and design problem, we are left with the design problem. In the design problem we need to determine the optimal sizing considering the capital and the operation cost subject to constraints. That is, we need to decide on the optimal diameter for gravitational and pumped pipelines, WWTPs and reservoirs volumes. Sizing the gravitational and pumped pipelines, WWTPs and reservoirs volumes depends on the input flows over the three seasons, taking into consideration the capital and operation costs subject to constraints.

The problem of optimal technology selection within the WWTPs was covered in the models developed in Section 3.1. As such, to complete the optimal design problem for the network we need a model that is able to find the sizing of the network components in conjunction to finding the optimal treatment train in the WWTPs.

3.2.2. Model Components

Decision Variables

The decision variables in the problem consist of 68 decision variables, 44 design variables and 24 operational variables. The 44 design variables are: 4 variables for diameters of gravitational pipelines, 4 variables for the diameters of the pressurized pipelines, and 36 treatment variables for the selection of the treatment train technologies in the four potential WWTPs (9 variables for each of the four potential WWTPs as required by the model in Equation 3.7). These 44 decision variables determine the design of the network and thus they are selected once for the three seasons.

The 44 design variables are of discreet nature, where the diameter variables are integers in the range of 1 to 9 to represent the selection of the diameter from a set of 9 possible diameters which we define in the knowledge database. The treatment train technology variables are integers with the range of 1 to 44 to represent the 44 possible technologies as explained in Section 3.1.6. For example, choosing diameter 1 means that the first diameter found in the list of possible diameters is chosen, which has been defined as 110 mm in the knowledge database. Similarly, when choosing technology 13 it means that the treatment "Low Loaded Activated Sludge w/o de-N+Sec. Sedim" is a component in the treatment train of a WWTP (see in Table 3.1).

Beside the 44 design variables, there are 24 operational variables which are the flows in the network through the three seasons. These are continuous variables with the range of the allowed flow in the network. The derivation of these variables will be explained in the following subsection. It is noteworthy that the size of the WWTPs and the size of the reservoirs are obtained as a function of the flow variables; consequently, there is no need to define the sizes of the WWTPs and the sizes of reservoirs as independent decision variables. For example, the reservoir volume is determined as the difference between the maximum volume and the minimum volume over the three seasons.

Constraints

For this model there are number of constraints, in addition to those described in the treatment train design models, mostly for designing and the operations of distribution network components, such as gravitational and pumped pipelines, WWTPs and reservoirs.

An important set of constraints is the water conservation law at the network nodes. To facilitate the definition of this constraint it is possible to represent the distribution network using graph theory concepts. The network can be represented as a directed graph consisting of N nodes connected by M edges. The topology of the network is represented by the incidence matrix A, where $A \in R^{N \times M}$ has a row for each node and a column for each edge. The nonzero elements in each row are +1 and -1 for incoming and outgoing edges respectively. The incidence matrix of the network is defined as the $M \times N$ matrix as given by Equation (3.9). For example, the three nodes network shown in Figure 3.19 can be represented by 3X4 incidence matrix as given in Equation (3.9). As seen in Equation (3.10), the first arc (i.e. column one in the matrix) starts at node 1 and ends at node 2, and for this we have entries of -1 and +1 at these two nodes, respectively. The 4th column in the matrix presents the "input" arc to the network and it has only one positive entry in the first row.

$$A_{ij} = \begin{cases} 1 & \text{If arc j end at node i} \\ \text{-1} & \text{If arc j starts at node i}\ ,\ 1 \le i \le m,\ 1 \le \text{j} \le \text{n.} \\ 0 & \text{otherwise} \end{cases} \qquad (3.9)$$

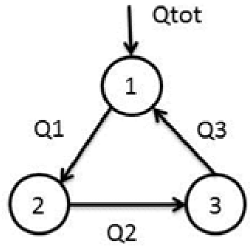


Figure 3.19 - Small example for incidence matrix

$$A = \begin{pmatrix} -1 & 0 & 1 & 1 \\ 1 & -1 & 0 & 0 \\ 0 & 1 & -1 & 0 \end{pmatrix} \quad (3.10)$$

Given the definition of the incidence matrix, the linear equation system in Equation (3.11) ensures the water balance in the network.

$$A \cdot Q = b \quad (3.11)$$

where A is the incidence matrix; *b is* a vector presenting the consumers and the incoming flow, and *Q* is a vector of the flows in the network.

The size of incidence matrix for describing the network in Figure 3.18 is $A \in R^{24\times48}$. Since there are more edges (i.e. columns) than nodes (i.e. rows) in the system (48 compared to 24), it is possible to extract dependent flow variables from the linear equation system and thus reduce the number of the flow variables in the model. Specifically, Equation (3.12) defines 24 dependent flow variables as a function of 24 independent flow variables. As such, instead of having 48 operational flow variables in the optimization model, we will only have 24 independent flow decision variables denoted as Q_{indep} in Equation (3.12).

$$Q_{dep} = A_1^{-1} \cdot (b - A_2 \cdot Q_{indep}) \quad (3.12)$$

where A_1 is a matrix of *N* independent columns of matrix A, A_2 is a matrix of *M-N* dependent columns of matrix A; Q_{dep} is the vector of dependent flow variables, Q_{indep} is the vector of independent decision flows.

Once the Q_{indep} variables are determined it is possible to define the dependent flow variables by using Equation (3.12). Other dependent variables are the size of the WWTPs and the size of the reservoirs, since these are obtained as a function of the flow variables. The size of the WWTP volume is determined as the sum of the volume in the three seasons while the size of the reservoirs volume is determined as the difference between the maximum volume and the minimum volume over the three seasons. When the difference is equal to zero, then there is no need to build a reservoir, but if it is greater than zero, it means one should be built.

In order to determine the optimal sizing for the gravitational pipelines, constraints such as maximum and minimum velocity and maximum capacity must be taken into consideration. Constraints for maximum velocity are for avoiding potential wear and tear due to erosion and abrasion, while minimum velocity is needed to avoid settling and sedimentation in sewage pipelines, which occurs in low velocities since the gravitational pipelines carry wastewater. The maximum capacity of gravitational pipelines is calculated using Manning's equation, Equation (3.13). Manning's equation is an empirical equation that applies to uniform flow in open channels and partially full pipe flows as in gravitational pipes. It is a function of the flow velocity, flow cross-section area and pipe slope.

$$v = \frac{1}{n} \cdot R^{2/3} \cdot J^{1/2} \qquad (3.13)$$

$$Q = v \cdot A \qquad (3.14)$$

where v - Flow velocity (m/sec); Q - Discharge (m^3/sec); A - Cross sectional area of the flow (m^2); N - Manning coefficient, a property of the pipe material; R =A/P- The hydraulic radius (m); P – Wetted perimeter (m); J - Pipe slope (m/m)

Maximum flow capacity constraint for gravitational pipeline consists of two components, one is calculated by the Manning equation for the maximum partially full pipe flow which is set to $(2r-h)/2r = 0.8$ in Figure 3.20, and the second is calculated also by the Manning equation, but allowed maximum velocity. The maximum flow capacity is determined by the minimum between these two. Choosing the minimum between the two capacities ensures that the flow is within maximum velocity constraint and a maximum partially full pipe flow constraint. The flow capacity for gravitational pipelines is given in Equation (3.15).

$$Q_{\max} = \max(Q_{\max}^{A}, Q_{\max}^{V_{\max}}) \quad (3.15)$$

where $Q_{\max}^{A}$ is the flow capacity according to the partially full pipe equation; $Q_{\max}^{V_{\max}}$ is the flow capacity according to the maximum velocity restriction. To calculate $Q_{\max}^{A}$ we use Equation (3.16) which defines the parameters of Manning's equation for open channel flow in partially full pipes. By setting $(2r-h)/2r = 0.8$, we calculate: θ, A, R which are then used in Equation (3.14) to calculate $Q_{\max}^{A}$. To calculate $Q_{\max}^{V_{\max}}$, we combine Equation (3.16) and Equation (3.13) and we set the velocity $v = V_{\max}$ to obtain one equation with one unknown h. The unknown h is then obtained by solving the equation numerically. By determining the solution h it will be possible to calculate $Q_{\max}^{V_{\max}}$.

$$\begin{aligned} r &= D/2 \\ \theta &= 2 \cdot \arccos\left(\frac{r-h}{r}\right) \\ A &= \pi \cdot r^2 - \frac{r^2 \cdot (\theta - \sin\theta)}{2} \\ P &= 2 \cdot \pi \cdot r - r \cdot \theta \\ R &= \frac{A}{P} \end{aligned} \quad (3.16)$$

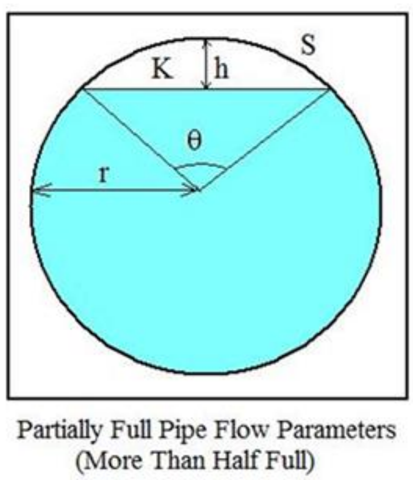


Figure 3.20 - Partially full pipe flow

To determine the minimum flow that satisfies the minimum velocity, $Q_{\min}^{V_{\min}}$, we combine Equation (3.16) and Equation (3.13) and we set the velocity $v = V_{\min}$ to obtain one equation with one unknown h. The unknown h is then obtained by solving the equation numerically. By determining the solution h it will be possible to calculate $Q_{\min}^{V_{\min}}$.

For a pumped pipeline the maximum flow capacity is calculated by the Hazen-Williams Formula given in Equation (3.17), which is valid for water and treated wastewater flowing through pressurized pipes. The maximum capacity is determined by defining a maximum hydraulic gradient $J_{\max}$ which the designer allows in the system.

$$Q_{\max} = \left(\frac{J_{\max}}{1.131 \cdot 10^9 \cdot D^{-4.87}} \cdot C^{1.852} \right)^{1/1.852} \tag{3.17}$$

where $J_{\max}$ is the maximum hydraulic gradient; $Q\ (m^3/hr)$ is the flow; C is Hazen-Williams coefficient; D (mm) is the diameter.

Non-negative flows constraints are needed in the model. Negative flows, may mean flowing in the opposite direction, but since the network, as described in Figure 3.18, is a directed network, changing flow directions is not allowed.

Objective Function

The objective function is used to drive the solution to minimum cost for the design of the system network and its operation over the three seasons. The total cost consists of Capital Costs, O&M Costs, and Energy Costs.

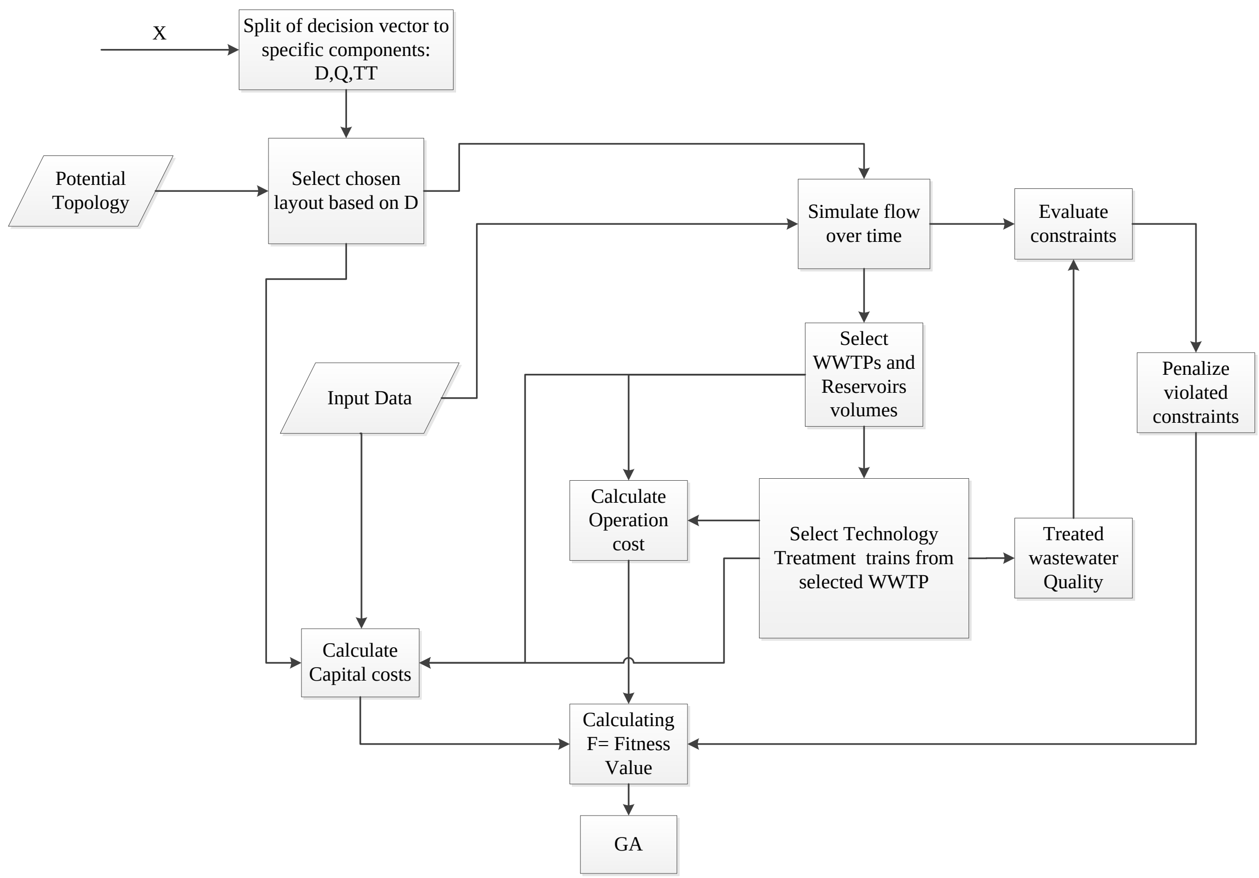
To solve the optimization problem we used a GA solver without explicitly adding the constraints in the solver. One way for dealing with constraints is using penalties for constraint violation. Since the optimization is performed by GA, which is a search technique, this does not add complication to the solution method, as would be the case in an analytical optimization method. When a constraint is violated in a GA evaluation, a penalty appears in the objective function whose magnitude is proportional to the amount of violation, multiplied by a penalty parameter. The penalty function is a method to approximate a constrained problem by an unconstrained problem structured such that minimization favors satisfaction of the constraints. As such, instead, we have added the constraints through a penalty function that converts the problem into an unconstrained optimization problem as shown in Equation (3.18).

$$\min_x \left[\text{cost(x)} + \text{P} \cdot \max(\text{g(x)},0) \right] \tag{3.18}$$

where x is the decision variables vector, $g(x)$ is the left hand side of the constraints of the type $g(x) \leq 0$ and P is a penalty factor.

GA is considered a black-box optimization solver, meaning that it does not require any information regarding the mathematical properties of the problem. For the GA to communicate with the mathematical model of the system it only requires the definition of an evaluation function. GA suggests different values for the decision vector, X, while the evaluation function returns the scores (i.e. cost plus penalty), F, of these solutions. The GA uses operators such as crossover and mutations, based on the scores obtained in successive generations, to create a "better" set of solutions for the problem. This search process continues until a convergence criterion is met.

For the GA to solve the model we need to define an evaluation function procedure which calculates the Capital Costs, O&M Costs, Energy Costs, and penalties from constraints violation. Figure 3.21, presents the objective function evaluation procedure which takes a potential solution, X, from the GA and returns the scores (i.e. cost plus penalty), F, of this solution.



Legend: D - Pipes diameters, possible number of diameters; Q – Independent flows, part of the decision variables; TT – Treatment train technologies for WWTP.

Figure 3.21 – The objective function evaluation procedure

The initial vector X is the user input data, used as the first solution of the GA. It contains 68 decision variables of the following types: (1) Diameters of gravitational pipelines; (2) Diameters of pumped pipelines; (3) Treatment train technologies; (4) The independent flows in the network.

Decision variables of diameters are allowed to have a very small value (close to zero) in all three seasons, which indicates that this link is not part of the optimal solution and will not be built. Setting minimum value of a decision variable, and not zero, is to avoid numerical difficulties. When a decision variable takes on this minimum value it means that the actual value is zero and the variable is removed from the output.

Equations for Calculating the Capital and O&M Costs

The following is a description of the equations used in this model for calculating the construction and maintenance of gravitational and pumped pipelines, and construction of reservoirs. The input data for the model includes: Sewage supply, Pipeline candidate diameters, Capital cost functions, O&M cost functions, Elevations of potential locations; Soil type and slope; Length of pipelines.

The capital costs of the WWTP are functions of its volume, which is determined in the optimization. The other parameters: average flow, Q_{avg}, peak daily flow, Q_{pday}, and dry weather flow, Q_{dwf}, are calculated as a function of the annual volume. This part was covered in Section 3.1.

Gravitational pipelines capital costs are calculated by Equations (3.22) and (3.23) which are taken from Brand and Ostfeld (2011) (Most of the equations used in this Section are taken from Brand and Ostfeld (2011), unless otherwise noted). There are two equations, since it is a function of the excavation cost and the cost of the pipeline itself, which is a function of the pipeline diameter and length. The excavation cost is a function of the depth of excavation, soil type, pipeline slope and the pipeline length.

The excavation depth is calculated in Equation (3.19). The areas for fill/excavation are calculated by Equations (3.20) and (3.21). Where, Equation (3.20) is for shallow excavation, i.e. $H1 < 4$ meters, and (3.21) is for deep excavation, i.e., $H1 > 4$ meters. The capital costs for a gravitational pipeline are calculated by Equations (3.22) and (3.23).

$$H1 = (J - J_s) \cdot L_g \cdot 1000 \tag{3.19}$$

$$A_1 = \frac{H1^2 - C_{\min}^2}{2 \cdot (J - J_s)} \tag{3.20}$$

$$A_2 = Lg \cdot C_{\min} + \frac{Lg^2}{2} \cdot (J - J_s) - \frac{H1^2 - C_{\min}^2}{2 \cdot (J - J_s)} \tag{3.21}$$

$$C_{pg1} = 21.6 \cdot D_g^{2.26} \cdot L + 7 \cdot A_1 \cdot L_w \tag{3.22}$$

$$C_{pg2} = 21.6 \cdot D_g^{2.26} \cdot L + 7 \cdot \frac{H_1^2 - C_{\min}^2}{2 \cdot (J - J_s)} \cdot L_w + 10 \cdot A_2 \cdot L_w \tag{3.23}$$

where, J and J_s are pipeline and soil surface slope respectively, L_g is pipeline length (km), C_{min} is the minimum pipeline depth (m), L_w is pipe excavation width (m), $H1$ is least excavation cost (m), A_1 and A_2 are excavation areas to and above a depth of $H1$ (m^2), respectively, C_{pg1} and C_{pg2} are construction costs for shallow and deep excavation ($/year), respectively.

The pumped pipeline capital cost as function of pipeline diameter and length is given in Equation (3.24).

$$C_{pp} = 382.5 \cdot D_p^{1.455} \cdot L \tag{3.24}$$

The energy cost is a function of the discharge, presented by Equation (3.25) (Housh, 2011).

$$\begin{aligned} CP_{energy} &= \frac{XP \cdot \left(\frac{Q}{w}\right)}{200} \cdot 0.736 \cdot w \cdot KWHC \\ XP &= \Delta Z_p + \Delta Hf \\ \Delta Hf &= 1.526 \cdot 10^7 \cdot \left(\frac{Q}{w \cdot c}\right)^{1.852} \cdot D_p^{-4.87} \cdot L \end{aligned} \tag{3.25}$$

where XP is the total head difference (m); Q is flow ($m^3/season$); w is number of pumping hours ($hr/season$); $KWHC$ is pumping cost ($\$/kwhr$); ΔZ_p is topographical difference (m); ΔHf is energy head loss (m); c is Hazen Williams coefficient ($-$); D_p is link diameter (cm); L_p is link length (km).

In addition, for a pumped pipeline there is a pump station construction cost which is given in Equation (3.26) (Housh, 2011). The pump construction cost is a function of total head difference XP.

$$C_{Cpump} = 64920 \cdot XP^{0.33} \tag{3.26}$$

Reservoir capital cost is a function of excavation cost which is calculated by Equation (3.27) (Joksimovic, 2006).

$$Cr = A_s \cdot V_{res} \tag{3.27}$$

The O&M costs for gravitational, pumped pipelines and reservoirs are percentage functions of capital costs as shown in Equation (3.28).

$$Co_g = 0.03 \cdot C_{pg}$$
$$Co_{pp} = 0.03 \cdot C_{pp} \qquad (3.28)$$
$$Cor = 0.03 \cdot Cr$$

3.2.3. Testing the Regional Planning Model of Wastewater Treatment System

In this Section we present preliminary tests[1] for the model, the model has been tested under various conditions, in order to check its validity and to investigate its performance under different conditions. In what follows we present a Base Run and one run of Sensitivity Analysis. The purpose of these runs is to test the response of the model to changing in the design conditions. We changed the quantity of sewage produced by the city relative to the quantity of effluents that is required by the consumer as follows:

Base Run: The influent supply is equal to the effluent demand for each of the three seasons. It is expected that the solution of the system will not introduce storage facilities.

Sensitivity Analysis Run: The supply is greater than the demand – storage will be required;

3.2.3.1. Base Run

The runs are made under the condition that the supply quantity exactly meets the demand in the three seasons. In this case, it is expected that the model will have an optimal solution without any reservoir, since there is no need to store water between seasons. The input data for this run is given in Table 3.12. The effluents will flow directly through gravitational pipes, and then go through treatment in the WWTP and through pumped pipeline to the end user. The solution is presented in Figure 3.23.

[1] As was mentioned previously, the main focus of this thesis is to develop a model that optimizes the treatment train. The regional model is a secondary product of this thesis.

Table 3.12: Base Run - Input Data

Variable Name	**Value**	**Description**
Qp (m^3/season)	60000	Source Flow
Qd (m^3/season)	60000	Demand Flow
Gravitational pipe lines elevation (g_node_el)	110,100,90,95	Wastewater treatment plant and Gravitational pipe lines suggested elevations
Soil_Id	1 or 2	Loam/Heavy Soil
L (km)	0.1	Distances: pipelines length
All_D (mm)	[110, 160, 200, 225, 250, 315, 355, 400, 0.001]	Pipeline candidate diameters
C_{min} (m)	1.5	Minimum pipeline depth

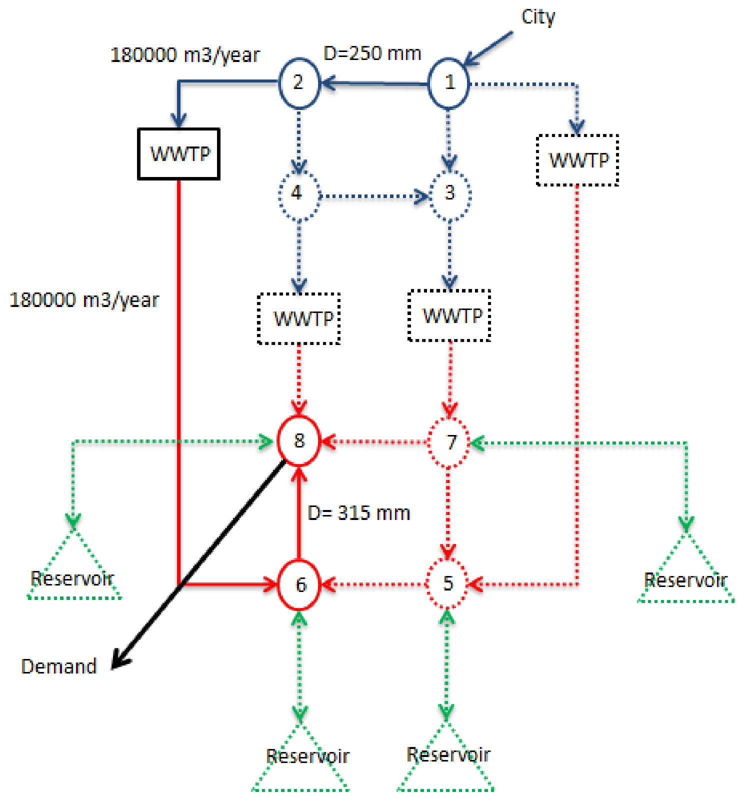


Figure 3.22 - The design problem for the Base Run

The optimal network is composed of gravitational pipeline, a wastewater treatment plant and a pumping pipeline as shown in Figure 3.22. In Figure 3.22 we can see the optimal design network, as a subset of the potential network layout, where the solid lines present the chosen components for the optimal network and the dashed lines present the non-chosen components which are not part of the optimal network for this Base Run.

This design is constant in time and does not change through the seasons. The optimal gravitational pipeline diameters are 250 mm and this diameter will be the same through the seasons. The pumped pipeline diameter is set to 315 mm and the WWTP capacity is set to 18,000 m^3 per year. As can be seen in Figure 3.23, there is no reservoirs in the selected design since the demand is exactly equal to the supply in the three seasons. For the WWTP design, the model selects an optimal treatment train. Table 3.13 details the technologies selected in the WWTP which is obtained in Base Run.

Figure 3.23 presents the operation problem of the network, where we can see the flow over the three seasons. A flow of 0.0058 (m^3/sec) is carried over by the gravitational pipeline, through the WWTP and the pumped pipeline to the consumer. Figure 3.23, presents two quality parameters, BOD and TN. We can see their concentrations in the influent at the start, before the wastewater treatment, and after the WWTP, where the concentrations are decreased.

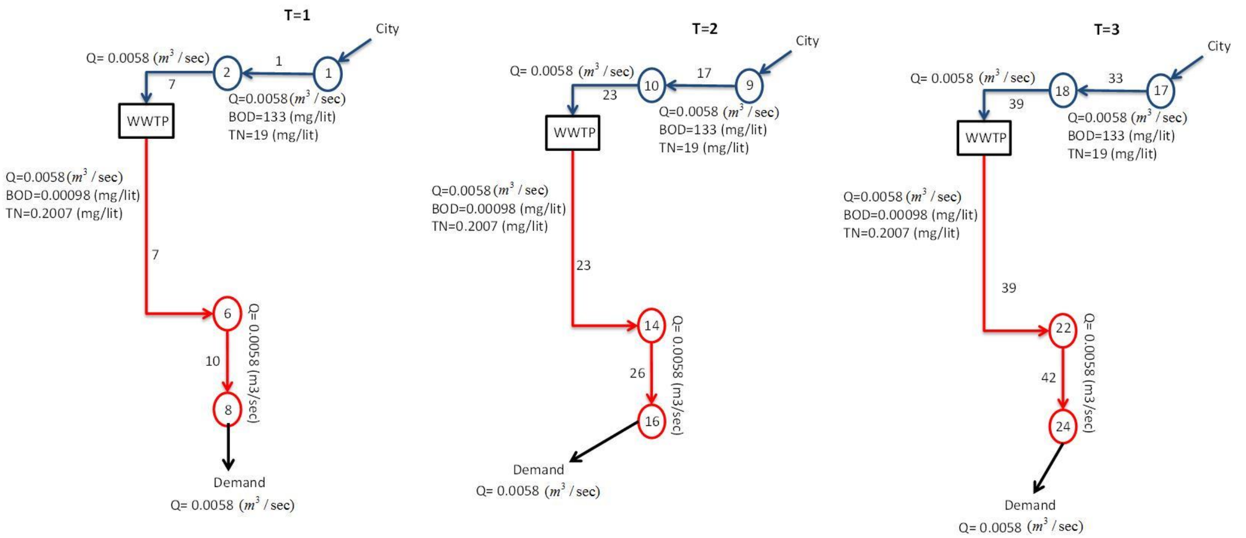


Figure 3.23 - Presenting the optimal network for Base Run

Table 3.13: The Treatment Train for the WWTP in Base Run

Stage	Selected Technology
1	None
2	Stabilization pond: anaerobic
3	Stabilization pond: aerated
4	Phosphorus Precipitation
5	Surface Filtration
6	Soil aquifer treatment
7	Ultra-Filtration
8	Ion Exchange
9	None

3.2.3.2. Sensitivity Analysis (SA)

Here we consider a situation where the supply changes through the seasons. The demand in season 1 equals the supply, in season 2 is less than the supply and in season 3 is more than the supply. Table 3.14 presents the input data for this run.

Table 3.14: Input Data for SA

Variable Name	Value	Description
Qp_1 (m^3/season)	60000	Source Flow
Qp_2 (m^3/season)	70000	Source Flow
Qp_3 (m^3/season)	90000	Source Flow
Qd_1 (m^3/season)	60000	Demand Flow
Qd_2 (m^3/season)	60000	Demand Flow
Qd_3 (m^3/season)	100000	Demand Flow
Gravitational pipe lines elevation (g_node_el)	110,100,90,95	Wastewater treatment plant and Gravitational pipe lines suggested elevations
Soil_Id	1 or 2	Loam/Heavy Soil
L (km)	0.1	Distances: pipelines length
All_D (mm)	[110, 160, 200, 225, 250, 315, 355, 400, 0.001]	Pipeline candidate diameters
C_{min} (m)	1.5	Minimum pipeline depth

In this case it is expected that the model will have to construct a reservoir in season 2, since the demand is less than the supply during this season. In season 3, the supply is less than the demand and the stored effluent from season 2 is used in season 3.

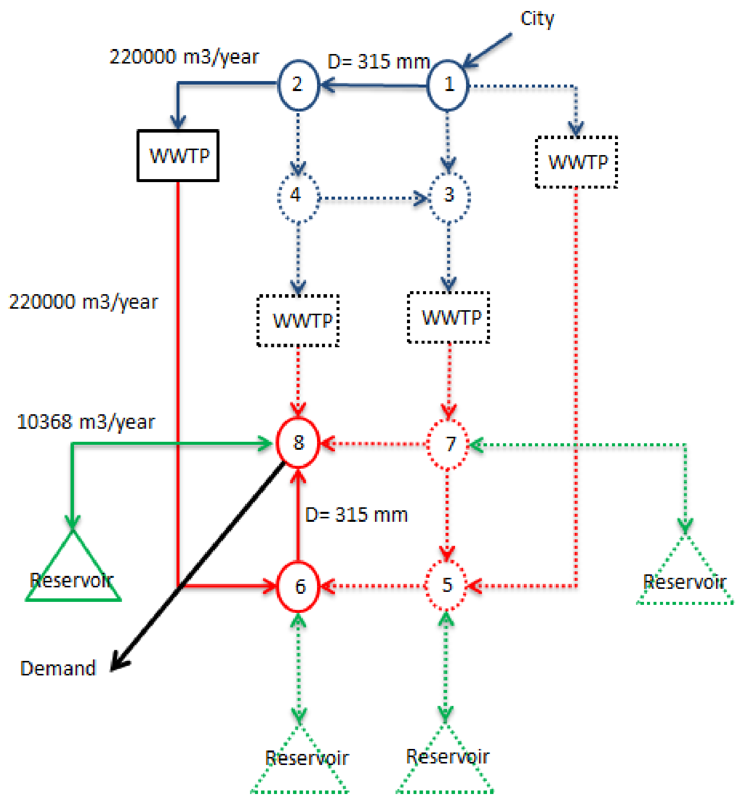


Figure 3.24 - Design problem for SA run in Season 2

In Figure 3.24, we present the design problem for SA in season 2. Unlike the previous run, here we have a reservoir which is built and added to the design problem. The design problem is constant and does not change through the seasons, meaning that if the reservoir is built on season 2, then the reservoir will be also in season 3, as we can in Figure 3.25. In Figure 3.24, we can see the gravitational and pumped pipeline diameters, the WWTP volume and the reservoir volume. The gravitational and pumped pipeline diameters are 315 mm, the WWTP volume is 220000 (m^3/year) and the reservoir volume in season 2, is 10368 (m^3/year). Since we did not change the influent and effluent quality over the seasons, the WWTP treatment train technologies for this SA are those of the previous run (Table 3.13).

In Figure 3.25, we can see the different flows through the seasons. In season 1, we can see that the flow in the gravitational and pumped pipelines were 0.0058 (m^3/sec), while in season 2, as a result of increasing the supply, the flow in the gravitational pipeline is increased to 0.0068 (m^3/sec), since the demand is still the same as in season 1, the flow in the pumped pipeline, did not change (i.e. 0.0058 m^3/sec), and the differences between the supply and the demand in season 2, goes to the reservoir. In season 3, the demand exceeds the supply, meaning that there is a need to use the water we have in the reservoir from season 2. The flow in the gravitational pipeline is increased to 0.0087 (m^3/sec), and the demand is 0.0097 (m^3/sec). Therefore, we use the effluents in the reservoir.

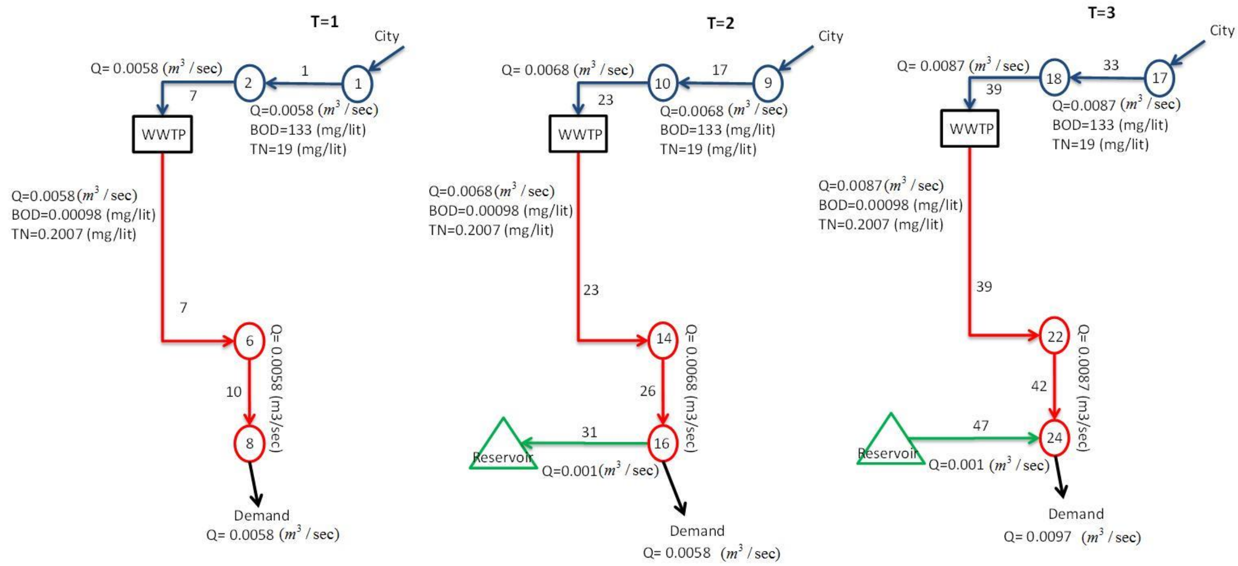


Figure 3.25 - Presenting the optimal network for the SA

4. Summary and Conclusions

4.1. DSS for Optimal Treatment Train Design

The literature review covered four main topics:

1. Wastewater treatment technologies;
2. Implication of reclaimed water irrigation on the crop yield and quality;
3. Regional wastewater treatment and reuse planning and management;
4. Decision Support Systems of wastewater treatment and reuse systems

Based on the findings in the literature we formulated a knowledge database for optimal design of a wastewater treatment train. The knowledge database was based mainly on Huang et al. 2013, Brand and Ostfeld, 2011 Joksimovic, 2006, and Oron, 1996. The knowledge database is generic and transportable to other locations and problems that deal with treatment of wastewater and reuse. In addition to the knowledge database, a series of four interviews were conducted with four Israeli researchers, about tertiary technologies such as Ultra Filtration (UF) and Reverse Osmosis (RO), information on the effect of using effluents with different qualities on plants and soil, information about the use of effluents for irrigation and information on the effect of using effluents on the plants, the soils and the environment.

The DSS for optimal design of the wastewater treatment train was developed in three phases. **Phase 1:** conceptual model, which describes generally what the model components are, and what the idea behind it is. **Phase 2:** a Five-Stages Model, which considered the selection of the treatment processes to be included in a treatment train of five stages (components) of an influent stream which has a given stream size, inflow quality parameters and the required maximum levels of these parameters in the effluent from the system. The five stages of the treatment train correspond to the five categories of technologies: 1) Preliminary treatment; 2) Primary treatment; 3) Secondary treatment; 4) Tertiary treatment; 5) Disinfection. The optimization model selects one technology from each of these five categories to construct a train of length five that is optimal with respect to the total capital, O&M and damage costs. For this model, we have developed two formulations, the first uses binary variables, where one binary variable presents each of the technologies in the knowledge database and indicates whether the technology is to be included in the optimal train or not. The second formulation uses integer variables, where an integer variable picks a technology in the five stages in the train. **Phase 3:** is the Unlimited

Stages Model, in which we considered an unlimited treatment train without a-priori fixed number of stages, unlike the Five-Stages Model. This change allows the model to choose any available technology consistent with the treatment train synthesis rules and thus facilitates a more generic representation of the treatment train combinations.

In order to solve the optimization problems, detailed in Section 3, we used Matlab's GA solver for searching the feasible domain. We used the GA solver without explicitly adding constraints in the solver. Instead, we added the constraints through a penalty function that converts a constrained optimization problem to an unconstrained one. Base Runs and Sensitivity Analysis runs were conducted for the different data to test how the selection of treatment train technologies is affected by changing the effluent quality standards, how this is reflected in the capital and O&M costs, and how damage cost functions of a quality parameter affect the optimal treatment train and the selected technologies.

4.2. Regional Planning Model of Wastewater Treatment System

The model developed in Section 3.2 determines the optimal network for distribution and treatment of wastewater. While the main focus of this work was to develop the treatment train optimal design DSS described is Section 3.1. As a secondary product of this thesis, and building on the treatment train optimization model, we started the development of a regional planning model of wastewater treatment system. This model takes into consideration the design and layout problem for optimizing a distribution network for the treatment facilities of wastewater and the conveyance/storage of treated wastewater to consumers.

The objective is to minimize total costs, which includes the WWTP costs, reservoir costs, gravitational and pumped pipeline costs and damage costs. The problem of optimal technology selection within the WWTPs was covered in the models developed in Section 3.1. As such, to complete the optimal design problem for the network we need a model that is able to find the sizing of the network components in conjunction to finding the optimal treatment train in the WWTPs.

The model contains two interconnected problems: the layout selection problem and the design problem. The layout selection problem is about finding which components, out of the set of potential components, should be present in the optimal solution. As such, one may think of the decision variables in the layout decision problem as binary variables indicating whether the component is “on” or “off”, but a better way was to delete components by allowing them to take on a very small non-negative value. The design problem is about finding the optimal sizing for the selected components in the layout problem. Determining the sizing of the different components requires calculating the flows in the system over time. Preliminary results from this model show that the model performs as expected when tested on illustrative conditions.

4.3. Conclusions

The results of testing the DSS developed herein illustrate the importance of developing such systems and how they can help in managing and planning the reclaimed water treatment and transport. The treatment train models provide a generic framework and flexibility for capturing the decision maker preferences. The Regional Planning Model provides an efficient approach for planning the layout, sizing and operating the components of a network; it addresses issues of seasonal distribution of reclaimed water and determines least-cost distribution system.

Using these models is relevant for decision makers to developed wastewater treatment systems for using effluents for irrigation. Incorporating the damage cost as part of the models, in addition to the capital and O&M costs, affected the results and the selection of the treatment train technologies, this highlights the importance of incorporating damage cost functions in the design process in addition to classical economical costs (i.e. capital and O&M).

In conclusion, it is expected that the methodologies developed and incorporated in this research will provide the planners of future water reuse schemes with a useful tool for exploring efficient designs of wastewater treatment systems.

4.4. Future Research

4.4.1. DSS for Optimal Treatment Train Design

- Including more advanced treatment technologies that can lead to better quality effluents.
- Incorporating other economic aspects besides those included in the model, such as, land requirements for a WWTP.
- Incorporating additional environmental considerations, such as odor generations, chemical requirements and impacts to groundwater.
- Incorporating a better modeling for the environmental damage evaluations caused by using effluents for irrigation.

4.4.2. The Regional Planning Model of Wastewater Treatment System

- Further testing the model developed herein to cover more scenarios.
- Expanding the distribution system to include more WWTPs, reservoirs and pipelines network.
- Adding water quality interactions within the water distribution systems components.
- Expanding the end-user properties, where also industries can use reclaimed water for industrial cooling.
- Adding uncertainty to the model's parameters and assess the impact of the uncertainty on the system design and operation.

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Appendix 1 - User Manual: DSS for Optimal Design of Wastewater Treatment System

Introduction

The purpose of the user manual is to help decision makers, engineers and who is going to use this Model, to follow the instructions, in order to obtain a successful run of the model.

The Model was programmed in Matlab with an Excel user interface, which serves for inputting the required data, which defined by the user. The Model consists of five files as shown in Figure 1.1. To run the Model the user should make sure that all these files are in the same directory when running Matlab.

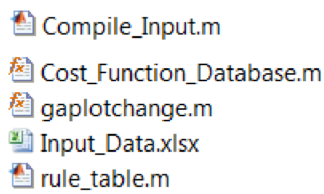

Figure 1.1 - The five files of the DSS

The files are: Input_Data (Excel file), Compile_Input (Matlab file), Cost_Function (Matlab file), gaplotchange (Matlab file) and rule_table (Matlab file). Each Matlab file contains a concise documentation that details its purpose and the data it contains.

Input_Data.xls: This file contains the input data needed for the model.

- Cost_Data: There is all the relevant cost data needed for the model.
- Quality_Data: Defining the quality data relevant for the technologies in the database. This file contains influent quality data and maximum values for the different quality parameters. Note that this file does not contain the removal relationship for a given technology; these are defined in *Compile_Input.m*.
- Damage_Data: Defining the damage cost as function of quality parameters concentrations, by the user. Each function is defined as a piecewise linear function with three segments (4 points).

Rule_table.m: This Matlab file defines the 45x45 matrix, which represents the treatment train synthesis rules.

Compile_Input.m: This Matlab file loads the excel sheet into Matlab's memory and contains the removal relationship for a given technology for all wastewater quality parameters.

Cost_Funciton.m: For a given treatment train, this function calculates the capital cost, the operation and maintenance cost, and the damage cost for the treatment train. For tested cases where the suggested train is not feasible a high penalty is added to the cost, and used as the fitness function in the Genetic Algorithm (GA) optimization solver to prevent this (infeasible) option from being selected. The main function is where the model evaluation occurs.

Here, in this Section, there is description of the main files. What each file includes and what data is needed for it.

Input_Data.xls:

Cost_Data: Contains the Cost Data for all technologies. Table 1.1 shows the parameters to be defined by the user.

Table 1.1, presents the user defining parameters, which are used in calculating the Capital, and O&M cost for all technologies. Given the parameters in Table 1.1, the costs will be automatically calculated, and the results are shown in Table 1.2. These calculations depend on the defining parameters in Table 1.1 that are placed in the Excel file.

Table 1.1: Parameters defined by the user

Parameter	Value
Qavg (m^3/day)	9500
Qpday (m^3/hr)	950
Qdwf (m^3/day)	8075
PE	26000
A (hectar)	1000
Vann (m^3/year)	140000
r (discount rate - %)	0.06
n (years)	25

where:

Qavg - Average daily flow (m^3/day)

Qpday - Peak daily flow (m^3/hr)

Qdwf - Dry weather flow (m^3/day)

PE - Serviced area population equivalents

A - Process area (hectare)

Vann - Annual processed volume (m^3/year)

r- Discount rate (%)

n- Planning period (years)

For example: the equation for calculating the capital cost of technology number 2 (Bar Screen) is: $11035 \cdot Qpday^{0.5138}$

Table 1.2: The Capital Cost and O&M cost for all technologies calculated depending on Table 1.1

ID of technology (Unit process)	Technology name	Capital Cost ($)	O&M Cost ($/year)
1	None	0	0
2	Bar Screen	373875	33828
3	Grit Chamber	422536	42254
4	Coarse Screen	598675	59867
5	Fine Screen	1130727	56536
6	Sedimentation w/o Coagulant	1522684	30454
7	Sedimentation w/ Coagulant	1786259	152302
8	DAF w/ Coagulant	621739	23219
9	Membrane Filtration	4749728	606876
10	Actiflo	4593298	303965
11	Stabilization Pond: Anaerobic	720553	49181
12	High Loaded Activated Sludge + Sec. Sedim	3204583	307069
13	Low Loaded Activated Sludge w/o de-N+Sec. Sedim	3931355	393136
14	Low Loaded Activated Sludge w/ de-N+Sec. Sedim	4133851	413385
15	Trickling Filter + Secondary Sedimentation	3621917	263493
16	Rotating Biological Contactor	3314276	564452
17	Submerged Aerated Filter	7368700	564452
18	Stabilization Pond: Aerobic	1269742	49181
19	Stabilization Pond: Aerated	316978	49181
20	Stabilization Pond: Facultative	1591515	49181
21	Constructed wetland: Free-Water-Surface Flow	266950	102602

22	Constructed wetland: Subsurface Water Flow	29920	102602
23	Membrane bioreactor	6667504	0
24	Excess Biological Phosphorus Removal	148360	8892
25	Phosphorus Precipitation	38745	18200
26	Filtration over fine porous media	311069	31981
27	Surface filtration	475031	71255
28	Micro filtration	1187432	11200
29	Ultra filtration	1187432	11200
30	Nano filtration	1966532	15400
31	Reverse osmosis	1966532	14560
32	Granular Activated Carbon	2126619	376216
33	Powdered Activated Carbon	4895	21000
34	Ion exchange	1066000	110240
35	Advanced oxidation -UV/O3	505189	21000
36	Advanced oxidation -UV/H2O2	505189	21000
37	Soil Aquifer Treatment	7840	17500
38	Maturation pond	352626	34039
39	Constructed wetland - polishing	58000000	25000000
40	Flocculation	58219	4152
41	Ozone	1721631	131232
42	Paracetic acid	1225324	42000
43	Chlorine dioxide	1225324	107647
44	Chlorine gas	1225324	154847
45	Ultraviolet radiation	479639	25200

Quality_Data: This sheet consists of the quality data relevant for the technologies. This data is used by the *Compile_Input.m* Matlab file, in order to calculate the effluent quality data for chosen technologies with given influent quality data and regulation standards.

Table 1.3, presents the defining of 10 quality parameters in the influent, which will be processed by the treatment train technologies.

Table 1.4 presents the effluent quality requirement at the end of each technology for four quality parameters, for example, where the user can define the effluent quality for all 10 quality parameters. When there is no limit on the quality variables then the user should input the value of the influent quality or any large value such as 1E+50.

Table 1.5 defines a set of parameters which are used to define the removal ratio functions for each technology and for each water quality variable in *Compile_Input.m*.

Table 1.3: Influent Data (Cin)

Turb (NTU)	TSS (mg/l)	BOD (mg/l)	COD (mg/l)	TN (mg/l)	TP (mg/l)	FC (#/100ml)	INEggs (#/100ml)	Ecoli (#/100ml)	Salinity (mg/l)
225	155	133	600	19	4	1.00E+06	800	1.00E+08	250

Table 1.4: Example of Effluent Maximum Requirement (Cmax)

Technology	Turb (NTU)	TSS (mg/l)	BOD (mg/l)	COD (mg/l)
1	1.00E+50	1.00E+50	1.00E+50	1.00E+50
2	1.00E+50	1.00E+50	1.00E+50	1.00E+50
3	1.00E+50	1.00E+50	1.00E+50	1.00E+50

Table 1.5: Coefficient defined by the user to formulate the treatment functions for each technology

Parameter name	Value
BODrem	115
HRT	1
Temp	21
kt	3.094
pH	7.5
n	1
q1	9.5
q2	950
Penalty (P)	1E+20

where:

Cin - Influent quality data

Cmax – Maximum allowed effluent quality

BODrem- BOD removed

HRT- Hydraulic Retention time = V/Q.

Temp - Temperature

Kt = $2.6*1.19^{(Temp-20)}$;

ph = 7.5;

n- Number of maturation ponds

q - Is calculated as q=Q/A, where Q is flow and A is area of constructed wetland.

For instance, if technology number 11 has been chosen as the first technology in the treatment train, the calculation of BOD concentration after using this technology is:

$$C^{11}_{eff} = 2 \cdot Temp + 20/100$$

These equations are defined in the *Compile_Input.m* file, where for each technology and for each quality parameter, there are such equations to define the removal relationship.

The quality equations are defined in *Compile_Input.m* file as shown in Figure 1.2. The database contains 10 quality parameters and 45 technologies, therefore for every technology, there are 10 different equations and 450 equations are defined in *Compile_Input.m*.

These relationships are defined as *handle function* Matlab variable called *fun_CellQ*. Each cell is defined for a parameter, therefore there are 10 cells. At each cell, there are 45 equations for the 45 technologies. The handle function is a function of the variable C, which present the concentration of each parameter from the previous technology.

```
fun_CellQ{3}{1}=@(C)C*(1-(0/100));
fun_CellQ{3}{2}=@(C)C*(1-(2.5/100));
fun_CellQ{3}{3}=@(C)C*(1-(4/100));
fun_CellQ{3}{4}=@(C)C*(1-(0/100));
fun_CellQ{3}{5}=@(C)C*(1-(2.5/100));
fun_CellQ{3}{6}=@(C)C*(1-(25/100));
fun_CellQ{3}{7}=@(C)C*(1-(50/100));
fun_CellQ{3}{8}=@(C)C*(1-(50/100));
fun_CellQ{3}{9}=@(C)C*(1-(82.5/100));
fun_CellQ{3}{10}=@(C)C*(1-(65/100));
fun_CellQ{3}{11}=@(C)2*Temp+20/100;
fun_CellQ{3}{12}=@(C)C*(1-(10/100));
fun_CellQ{3}{13}=@(C)C*(1-(7/100));
fun_CellQ{3}{14}=@(C)C*(1-(5/100));
fun_CellQ{3}{15}=@(C)C*(1-(60/100));
fun_CellQ{3}{16}=@(C)C*(1-(20/100));
```

Figure 1.2- The quality equations defined as function handles in Compile_Input.m

Damage_Data: This sheet consists of damage costs data, which calculated as a function of the quality parameters concentrations. These functions capture the total damage caused by the (lower than perfect) quality of the effluent – loss of crop yield, soil and water pollution. Each function is defined as a piecewise linear function with three segments, connecting 4 points. Once the four points are defined for each quality variable a graph which shows the damage function is created with these data. Tables 1.6 and 1.7 are describing the four points for each quality parameters, which are defined by the user. These four points define the three segment of the piecewise damage function.

Table 1.6: Concentration points at which the value of the damage function is given in Table 1.7

Parameter Name	Turbidity	TSS	BOD	COD	TN	TP	FC	INEggs	Ecoli	Salinity
Point 1	1	20	30	40	10	0.1	100	350	100	100
Point 2	2	35	70	80	15	1	150	1000	1000	150
Point 3	3	75	150	120	44	6	200	10000	10000	360
Point 4	4	100	340	200	76	20	1000	150000	100000	500

Table 1.7: Example of Damage function in ($)/ ($m^3$/day) at four points of the concentration value

Parameter Name	Turbidity	TSS	BOD	COD	TN	TP	FC	INEggs	Ecoli	Salinity
Damage @ Point 1	100	15	100	70	5	5	40	45	100	0
Damage @ Point 2	75	20	120	85	15	10	78	55	120	0
Damage @ Point 3	35	35	150	140	25	45	97	65	150	150
Damage @ Point 4	35	50	340	200	46	85	120	80	180	800

After filling these tables, the user gets the graphs for each quality parameter, as shown in Figure 1.3. Figure 1.3 presents how the BOD concentration can affect the cost function due to loss of the crop yield or its value, to soil and water pollution.

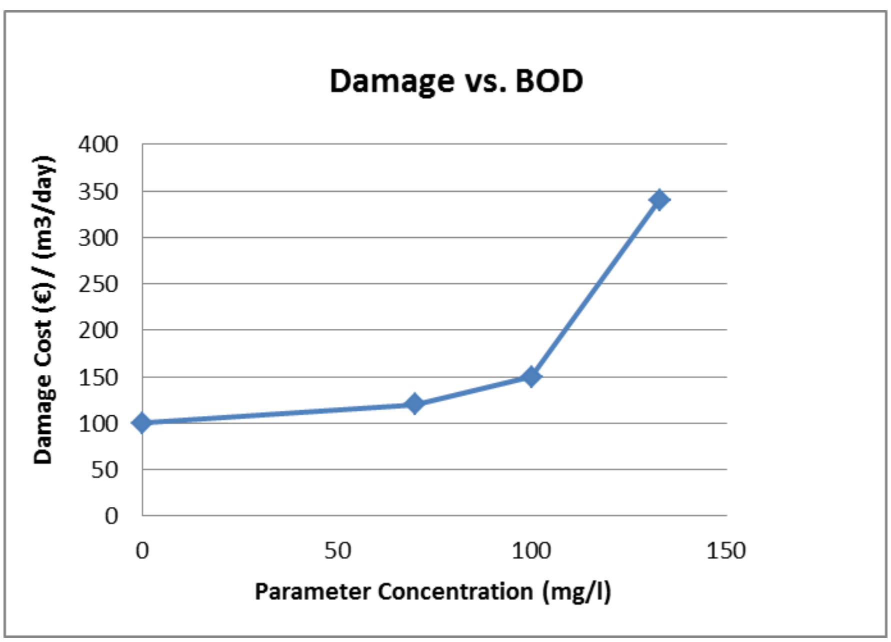

Figure 1.3 – Damage cost as a function of BOD concentration

The optimization app:

Running the model depends on using the GA optimization method, which is in the Apps toolbar, Figure 1.4. Upon pressing 'optimization' a large window appears, divided to two smaller windows. The right window is the 'Problem Setup and Results' while the left window is 'Options', Figure 1.5.

Figure 1.4- The APPS options

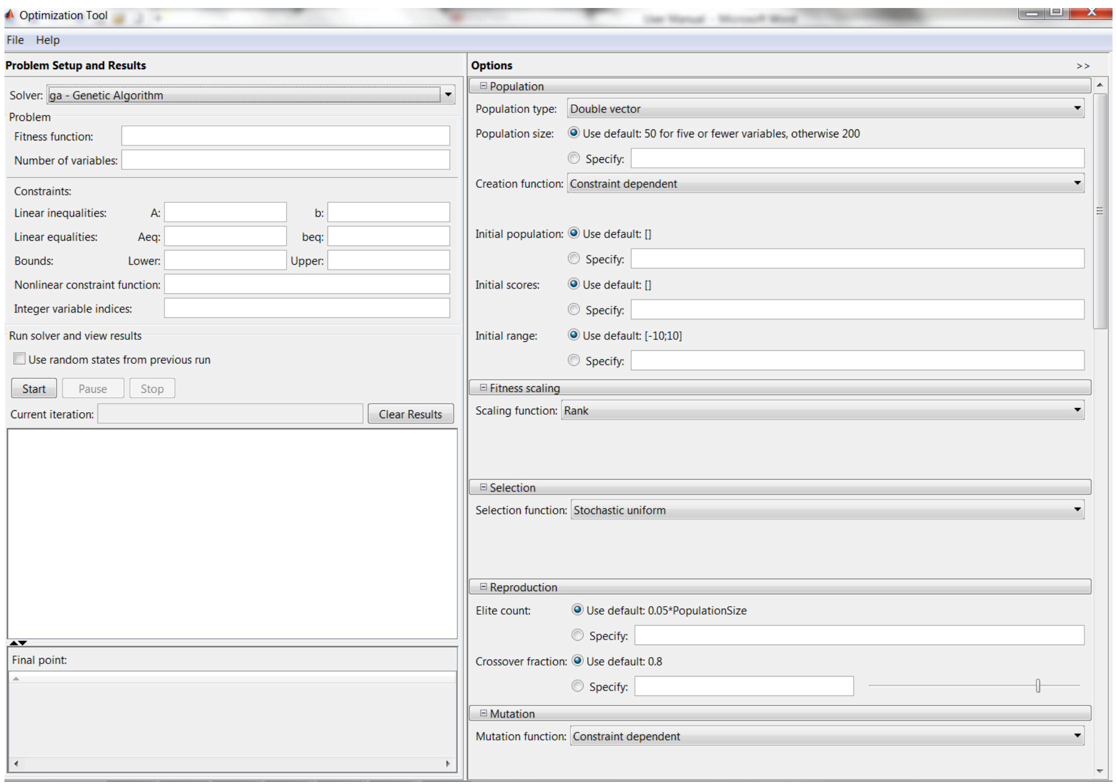

Figure 1.5 – The optimization tool window

Problem Setup and Results window:

This window, the left one in Figure 1.5, is also divided to two smaller windows: one for defining the problem and the constraints and the second is for the 'Run solver and view results'.

The first window is for choosing which optimization method you as a user would like to use. For running this model, choosing GA - Genetic Algorithm in the Solver option is the right optimization method. The next step, is writing down the objective function in the 'Fitness function' row and the number of decision variables, such as, the eight numbers of the technologies set for each of the eight stages in the treatment train.

The objective function is "Cost_Function", where the input variables for this function are:

T – The treatment train technologies
Ccapital - Capital costs, Com - O&M costs,
fun_CellQ - handle function for calculating the quality data
Cin - the influent quality, Cmax - the regulation standards
P - The penalty function
X_Data - x data for the calculation of the damage cost
Y_Data - y data for the calculation of the damage cost
Number of variables: the number of decision variables is equal to the number of technologies in a treatment train, which is defined by the user.

In addition, to defining the objective function and the number of decision variables, defining the constraints, in the constraints window. Writing down the constraints should be done as presented in Figure 1.6 below. Defining the upper and lower boundaries for the decision variables, and which of them are integer variables.

The bounds: The lower bound is defined as the lowest ID number of the technologies and the upper bound is defined as the maximum ID number of the technologies. Since, as a user there is no possible way to select an ID number that does not exist in the technologies database.
The first technology in the treatment train must be 1," None", since there are starting technologies that the treatment train should start with. Therefore, this condition can guarantee starting with raw influent.
Integer variables: All the decision variables in the model are integers; as such defining this field as 1: N, where N is number of technologies in the treatment train.

At first, when opening this window, the results window is still blank, since the model has not been run yet. All the changes, which as a user should be made, are marked by red rectangle in Figure 1.6.

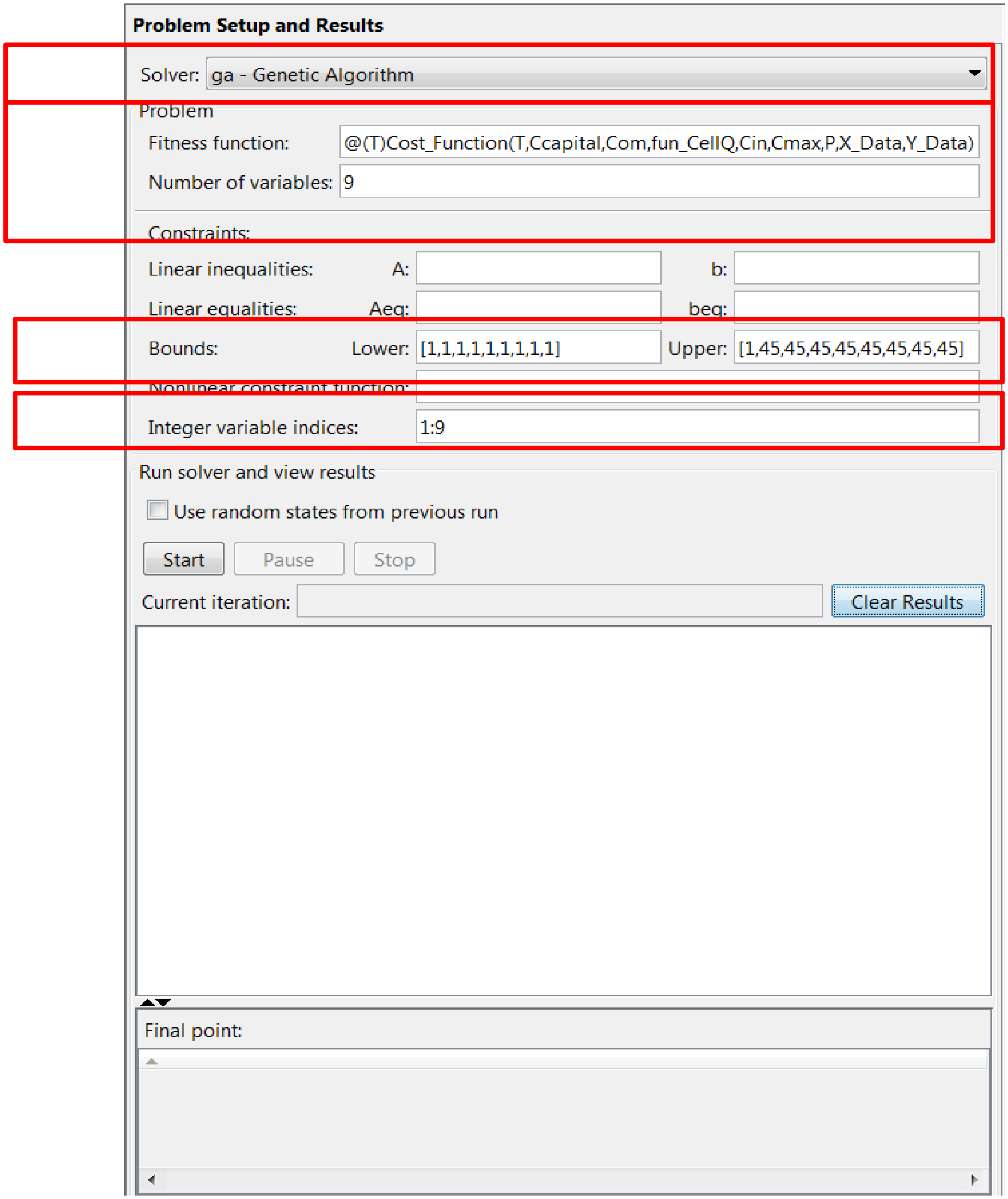

Figure 1.6 – Problem Setup and Results changes

'Options' Window:

Options window is for changing the default options for the GA algorithm:

- GA population size: defining, Max [Min(10* number of variable = 8*10, for example), 100], 40]

- Initial population: a set of 9 numbers, indicating which technology is placed in each stage as a starting point for the GA search (in the example below 1, 2, 7, 25, 29, 35, 37, and 42). This may be a random selection, just to start the algorithm, or it may be a treatment train that seems to the user to be a reasonable choice. The initial choice should not affect the final outcome although it may, since GA does not guarantee that the global optimum will be found. Adding an initial population is optional.
- Stopping criteria: Changing 'Generations', 'Stall generations', 'Function tolerance' and 'Constraint tolerance'.

Changing the population size and stopping criteria is necessary to the running efficiency of the model. These changes, mentioned in Figures 1.7, 1.8, 1.9 below, pointed out by the red rectangles.

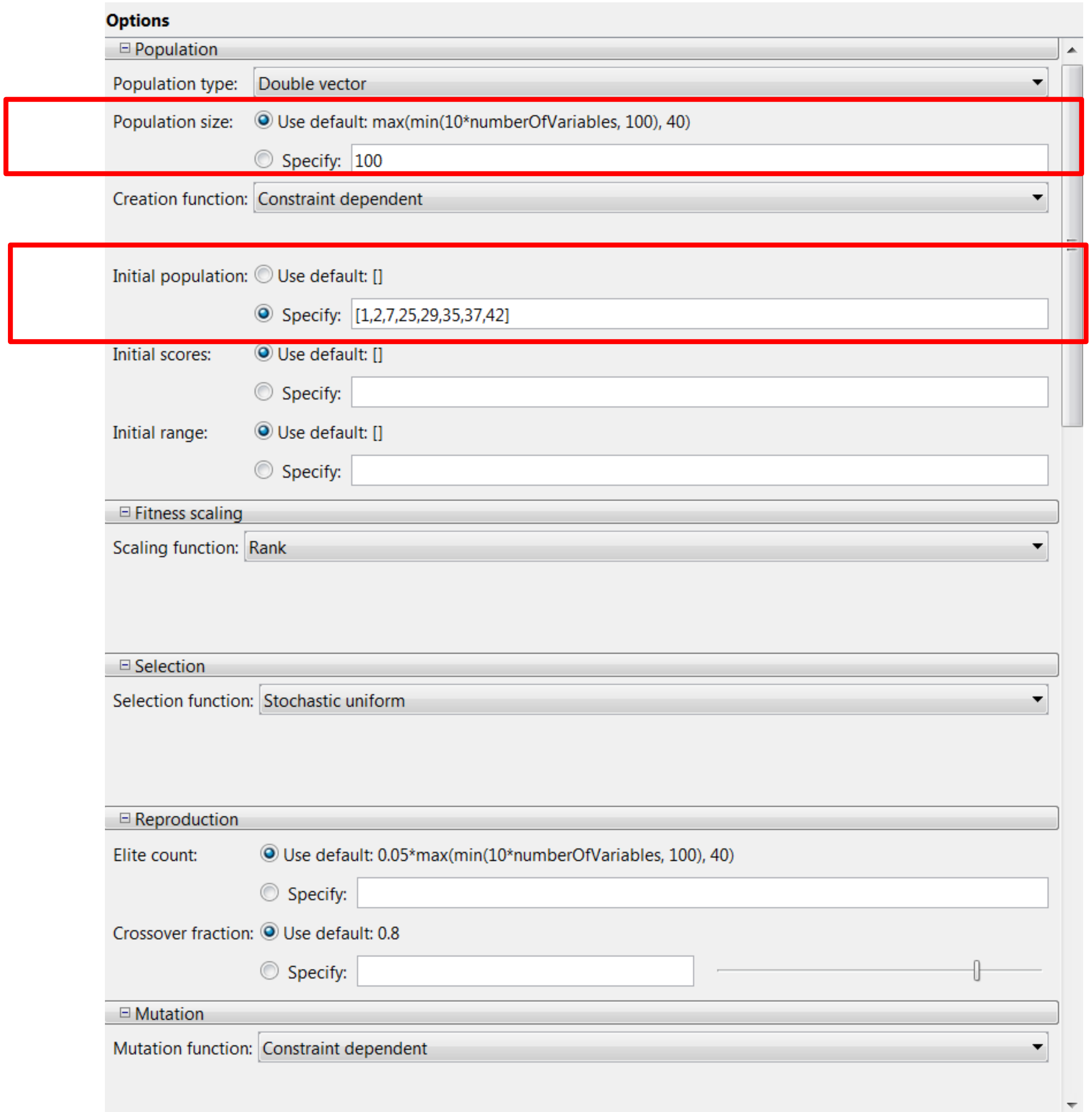

Figure 1.7 – Changing Population Size and Initial Population

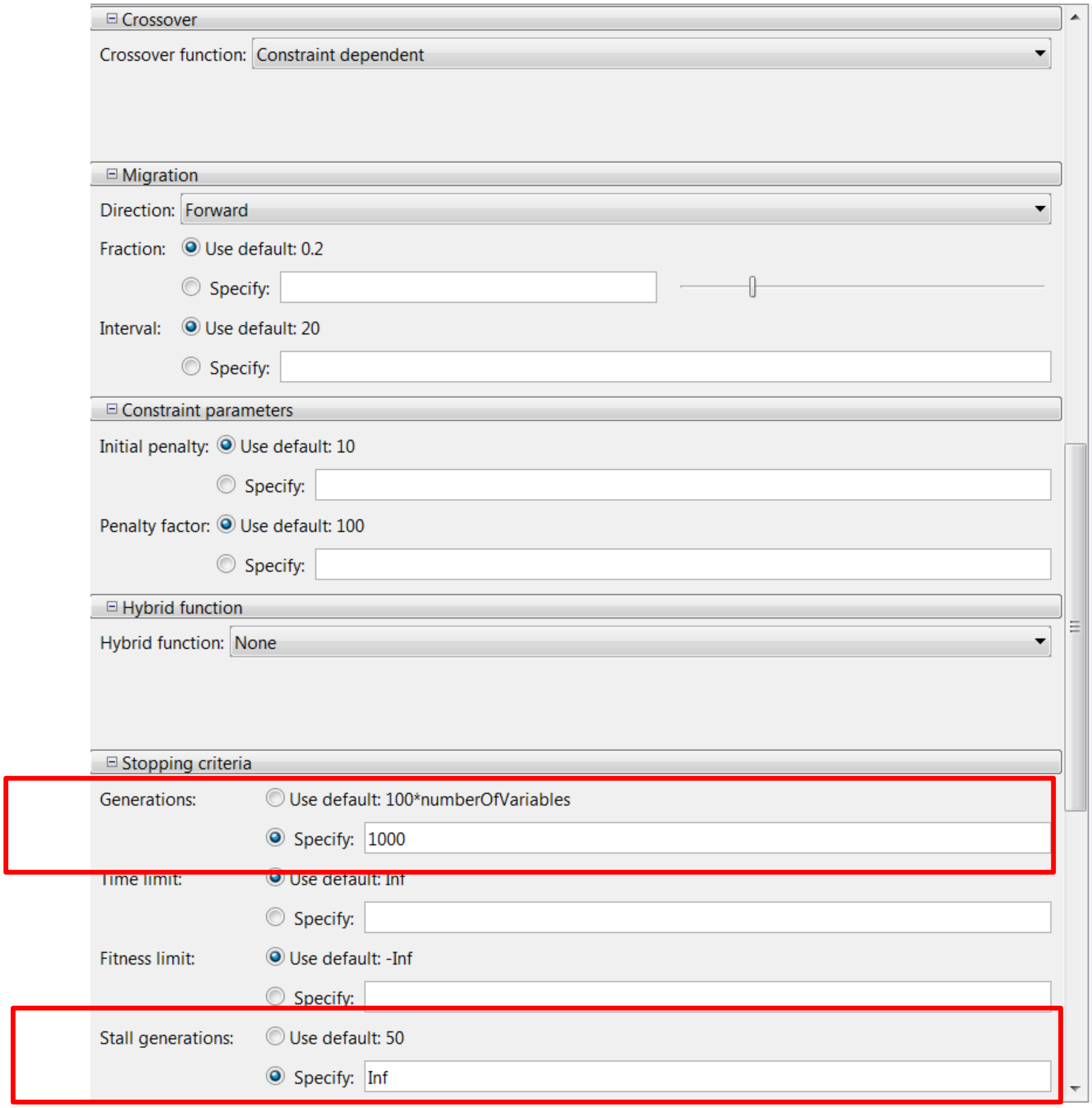

Figure 1.8 – Changing Parameters in the Stopping criteria

Adding the 'gaplotchange' function is a custom function in the 'Plot functions' option.

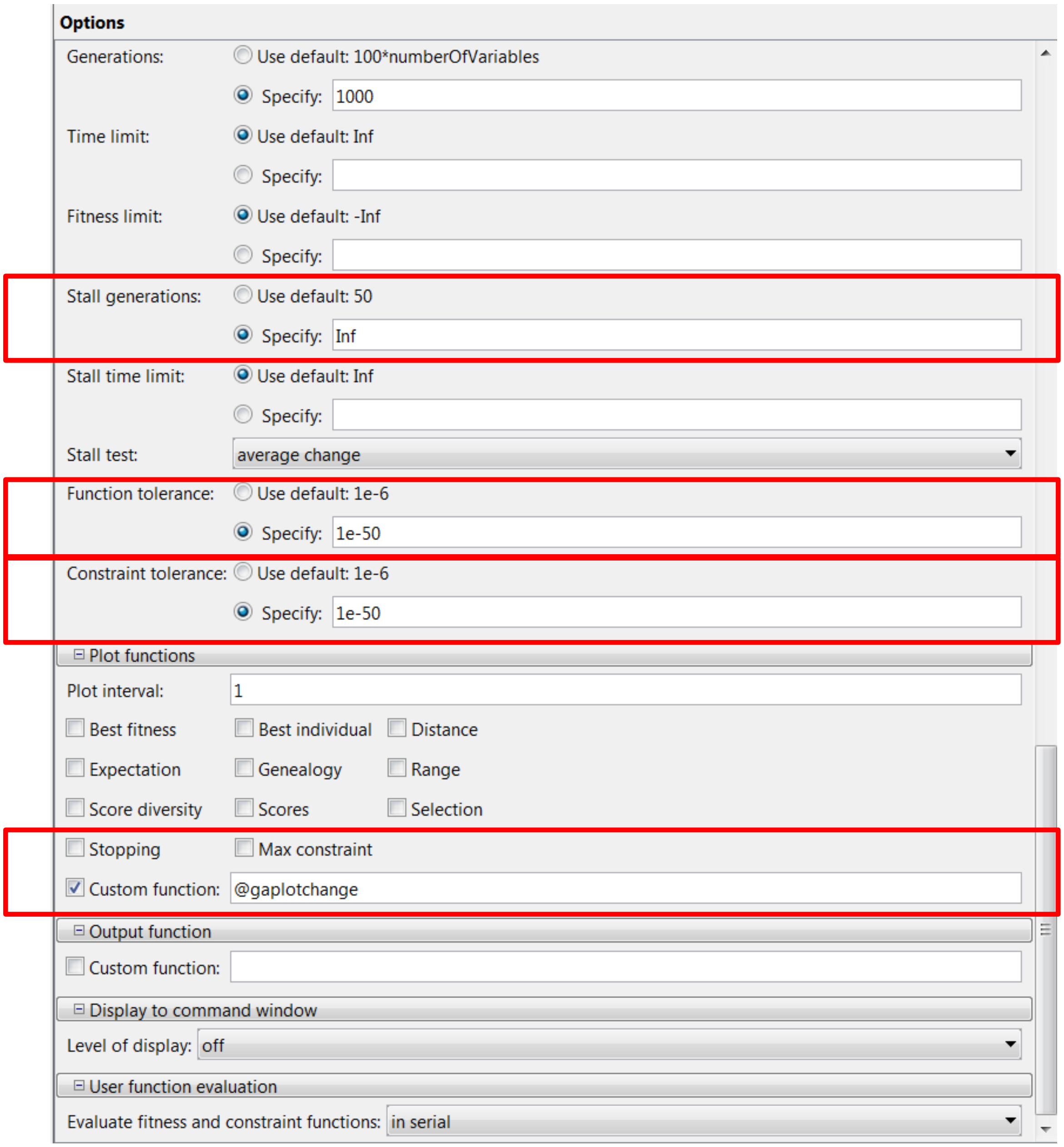

Figure 1.9 – Changing Parameters in the stopping criteria and plot functions

After changing the options, the user can run the model, by pressing 'Start'. Running the model takes usually about 15 minutes in average, then the final answer in the 'Run solver and view results' window is appeared, as presented in Figure 1.10 below.

The objective function value, Z, marked by the second red rectangle, is the minimum total cost and the 'Final point' is the optimal treatment train.

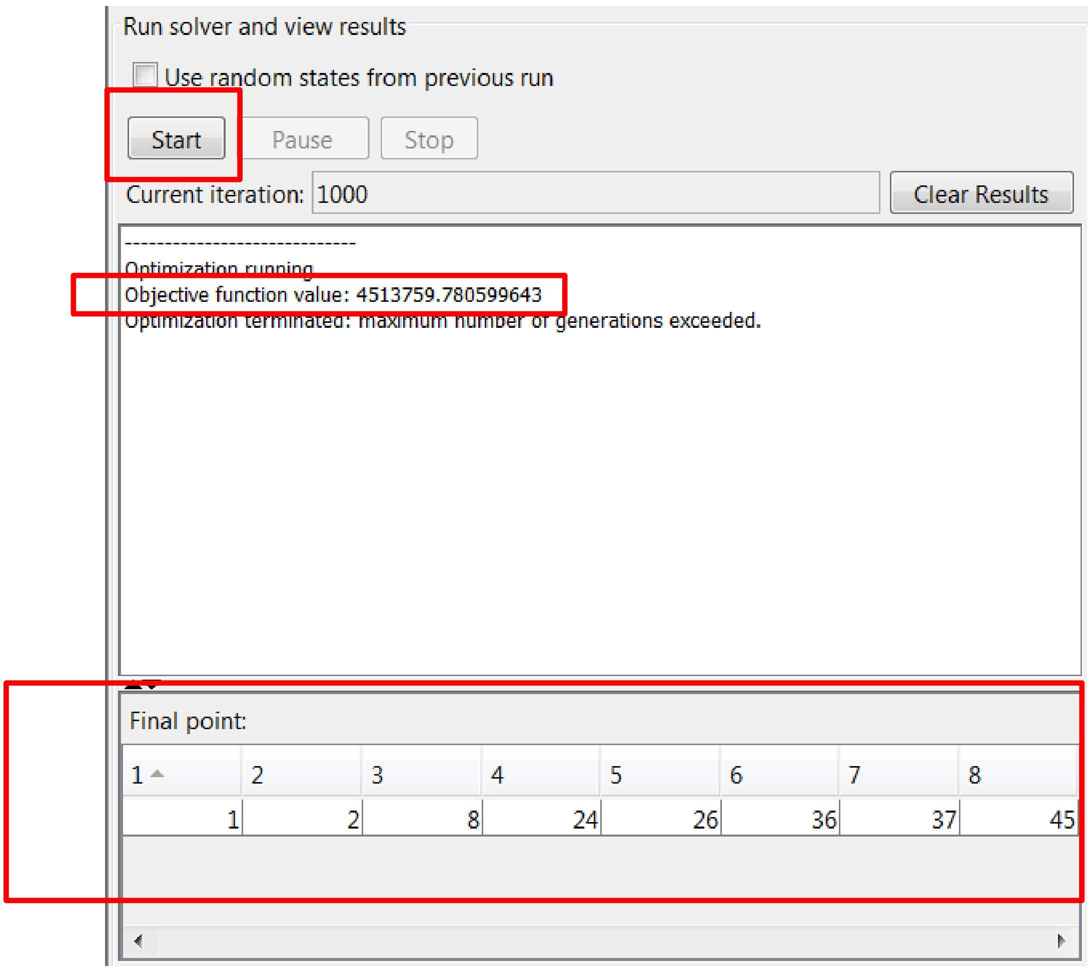

Figure 1.10 – Run solver and view results after running the model

While running the model, there is a popping window, which shows the progress of the solution as shown in Figure 1.11.

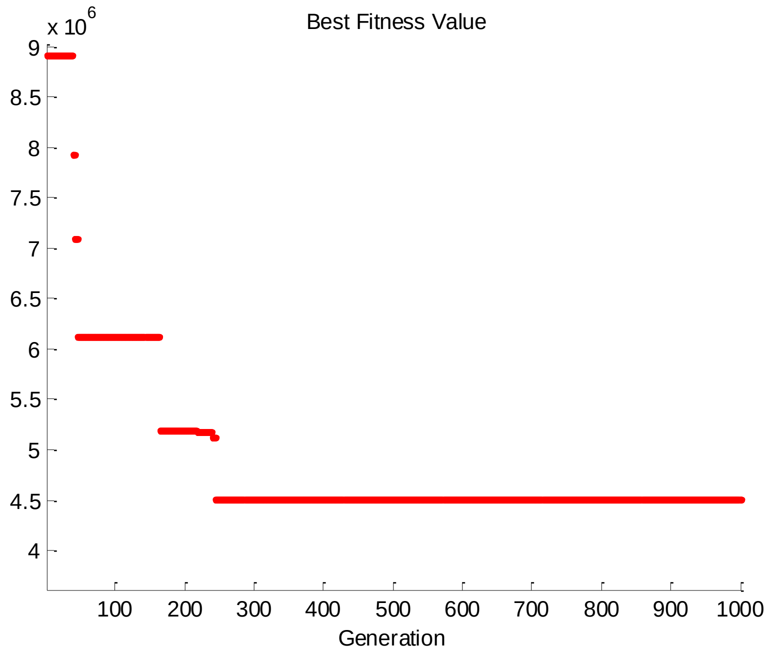

Figure 1.11 - 'gaplotchange' function's figure

The red line in Figure 1.11 is changing, within each iteration, until reaching the optimal solution. In the example shown in Figure 1.11, the value of the initial (input) solution is about $ 9E+6. It drops to 4.5E+6 in the first 230 iterations, in several steps, then stabilizes for the rest of the search and ends after the required 1000 iterations. The constant value for so many iterations indicates that this is the global optimum of the problem.

Appendix 2 – Questionnaires for Interviews (Hebrew)

שאלות עבור קבוצות החוקרים השונות:

קבוצת אבי שביב ואלכס פורמן, ההשפעות הסביבתיות, לקרקע ולצמח, כתוצאה מהשימוש במי קולחים להשקיה חקלאית:

- האם ניתן לנסח פונקציית מטרה כמותית להשקיה בקולחים משודרגים, למשל במונחים של השפעה על ערך הגידולים, ו/או במונחים של הנזק לקרקע ולסביבה?
- מהן הפונקציות והפרמטרים המקשרים בין איכות הקולחים ושיטת ההשקיה לבין התועלת (התפוקה החקלאית, הקטנת נזקים לקרקע ולסביבה) והעלות (של הטיפול ושל שיטת ההשקיה). אלו פונקציות המטרה (תועלת, עלות) וייתכן שישולבו לפונקציית מטרה אחת של תועלת נקיה (נטו).
- מהם האילוצים המגדירים את מרחב ההחלטה של איכות הקולחים ודרכי השימוש בהם?
- מה הם הפרמטרים שכדאי לבדוק ולאפיין על מנת שאוכל לדעת האם הקולחין עומדים בתקנים של השימוש ללא הגבלה ?
- מה הם הפרמטרים שאני צריכה במודל על מנת לאפיין, להגדיר ולהעריך את התפוקה החקלאית או את התועלת הסביבתית ?
- למה בחרתם בקרקעות-אדמות שהיו מושקות במי קולחין למשך זמן רב ולא בקרקעות נקיות המועמדות להשקיה במי קולחין?
- איך נקבעו שלושת הטיפולים המיועדים להשקיה ? עמ' 11 בהצעת הפרויקט.
- מה ההבדל, מבחינת ההשפעה על יבולים ועל נזקים סביבתיים, בין: membrane treated effluent לבין membrane treated effluent but with elevated applied P ?
- איך שיטת ההשקיה תשפיע על הנזק הסביבתי הנגרם כתוצאה מהשקיה במי קולחין ?
- מהי שיטת ההשקיה הנפוצה ביותר שנעשה בה שימוש להשקיה במי קולחין ?
- האם עלולים להתפתח נזקים סביבתיים לאור ההשקיה המתמשכת בקולחים שלישוניים ?
    - במידה וכן, האם ישנו צורך בהחמרת התקנות הקיימות היום ?
- השקיה בקולחים שלישוניים תתבצע בקרקעות שהושקו בעבר בקולחים שניוניים ?
- האם תהיה בדיקה עבור ההשקיה במי קולחים שלישוניים בשיטות ההשקיה השונות ?
- האם ניתן להעריך מספרית את עלות ההפחתה בנזק הסביבתי ?

קבוצת רפי סמיט וקרלוס דוזורץ, מידע על טכנולוגיות טיפול, טיפול שלישוני וטיפול בממברנות:

- מהן הפונקציות והפרמטרים המקשרים בין סוג הטכנולוגיה/סוג הטיפול לבין איכות הקולחים והעלות (של הטיפול).
- מדוע בחרתם את הטיפול הממברנלי, מה היתרונות והחסרונות ? ובמה הוא עדיף על טיפולים אחרים, כגון SAT?
- האם נבדקה הכדאיות הכלכלית לשימוש במערכת היברידית לעומת טכנולוגיות ופתרונות אחרים ?

- עד כמה בעיית הפאולינג משפיעה על הכדאיות של הטכנולוגיה הזו ? ואיך ניתן להעריך אותה כלכלית ?
- מה בדיוק תפקיד המסנן Clay micelles ולמה הוא נחוץ ?
- מדוע תהליך הרחקת הכלור לאחר טיפול UF ולפני RO חשוב ?
- מה החשיבות של תכנון הזמן המינימלי של שטיפת וניקוי הממברנות (backwash) ?
- מה היה השיקול שלכם לעבוד עם שתי מערכות של אוסמוזה הפוכה בטור ? מערכת אחת לא הייתה מספקת ?
- מהם ערכי הפרמטרים המאפיינים את איכות מי הקולחין לאחר הטיפול השלישוני המוצע? (UF ושני שלבים של RO).
- האם הטיפול המוצע נראה לכם מבחינה כלכלית ליישום בכל מט״שי הארץ, או אולי רק בחלק מהם ?
- מהו תחום היעילות האפשרי של תהליך הטיפול של ה- UF ?
- מהן השיטות שנעשה בהן שימוש היום להרחקת הזרחן ? אם יש אלטרנטיבות שונות מה ההבדלים ביניהן - - ביישום ובעלות?
- מה הפתרון היעיל והזול ביותר שאתם מציעים לבעיית הפאולינג ?

שאלות לקבוצת שרות השדה:

א. השיטות המקובלות בהשקיית קולחים:

א. האם החקלאים מבצעים טיפול כלשהו בקולחים לפני השימוש בהם (סינון, תוספת דשן לקולחים עצמם, ...) ?

ב. מהי שיטת ההשקיה הנפוצה בקרב החקלאיים עבור מי קולחים ?

ג. האם שיטת ההשקיה בהצפה עדיין בשימוש היום בקרב החקלאיים ?

ד. האם ההשקיה במי קולחים מבוצעת עבור סוגים מסוימים של גידולים ? אם כן, עבור איזה גידולים ומדוע ?

ב. תפוקה חקלאית:

א. איך היא מוגדרת ? טון לדונם ? וייחוסה לאיכות הקולחים ושיטת ההשקיה – בשטח ספציפי, באזור, ברחבי המדינה.

ב. האם ניתן להעריך את העלייה/הירידה ביבול כהשפעת איכות הקולחים ושיטת ההשקייה ?

ג. האם יש נתונים על התפוקה החקלאית בשטחים מוגדרים ובכמות כוללת אזורית שניתן לייחס אותם לאיכות הקולחים ולשיטת ההשקיה בקולחים.

ג. התועלות של שימוש בקולחים, יחסית לשימוש בשפירים (כולל התייחסות לזמינות ומחיר):

א. כיצד משפיעים מחירי השפירים והקולחים (שניוניים, שלישוניים) על החלטות החקלאים באשר לשימוש בסוגי מים אלה ולתחלופה ביניהם.

ב. איך מודדים את התועלת, באיזה פרמטרים?

ג. מהן הפונקציות שבעזרתן ניתן לתאר את התועלת?

ד. הנזקים של השקיה בקולחים:

א. מהם הנזקים של השקיה בקולחים בטווח קצר, בינוני, ארוך – לקרקע, למשאבי המים, לאוויר.

ב. מה מנוטר ונמדד, האם יש מאגרי נתונים?

ג. האם ניתן לחשב את הנזקים כפונקציה של איכות הקולחים (היתרון של קולחים שלישוניים לעומת שניוניים).

ד. האם "איכות הפרי" כתוצאה מהשקיה במי קולחים מוגדרת כנזק סביבתי או כחלק מהפגיעה ביבול/ איכות היבול ? ואיך ניתן להעריך דבר כזה ?

ה. איך ניתן לתאר את הנזק של מבנה הקרקע ? התלוי בערכי ה- BOD וה- SAR.

ו. האם בעיית החנקן כתוצאה מדישון יתר עדיין נפוצה בקרב החקלאיים ? איך ניתן לתאר אותה בעזרת פונקציה מתמטית.

מערכת קבלת החלטות לתכנון אופטימלי של מערכות לטיפול בשפכים

מרים אבו ואסל אגבאריה

תקציר

המחסור במים באזורים צחיחים למחצה כמו ישראל ומקומות אחרים בעולם מניע את הצורך בחיפוש אחרי מקורות מים אלטרנטיביים כגון מי קולחין, המשמשים בעיקר להשקיה חקלאית. החל משנת 1953 ישראל ניסחה את התקנות והסטנדרטים הראשונים לשימוש חוזר במי קולחין ומאז הנושא המשיך להתקדם ולהתפתח. עם זאת, עד שנת 1970, השימוש במי קולחין במדינה התבסס בעיקר על פרויקטים קטנים מבודדים ללא מדיניות ברורה בנושא. מאז תחילת שנות ה- 70, ישראל תכננה ויישמה בצורה אינטנסיבית את השימוש במי קולחין להשקיה חקלאית כך שהיום השימוש החוזר במי קולחין להשקיה עומד על כ- 75% מסך השפכים, כאשר רוב השימוש במי הקולחים הוא בחקלאות. הטיפול בשפכים והפיכתם למי הקולחין מתבצעת ע"י 135 מפעלים (מט"שים) המטפלים בכ- 355 מיליון מ"ק בשנה. כאשר כמות זו מהווה כ- 31% מסך המים המסופקים לחקלאות וכ- 18% מסך המים המסופקים בכל המדינה לכל השירותים. מטרתה של רשות המים, בהתאם לתכנית משק המים, להגיע לניצול של 95% ממי הקולחין לשימושים השונים תוך 5 שנים (רשות המים).

כתוצאה מן המגוון הרחב של טכנולוגיות אפשריות בכל אחד משלבי הטיפול (קדם, ראשוני, שניוני, שלישוני, חיטוי), והדרישות לאיכות הקולחים יש מספר גדול של חלופות לשילוב בין הטכנולוגיות הבונות את מערכת הטיפול. מכאן נובע הצורך בפיתוח מודל תומך בקבלת החלטות שיעזור למתכננים ולמקבלי ההחלטות בנושא.

המטרה העיקרית של המחקר המוצג בעבודה זו היא לפתח ולבדוק מודל אופטימיזציה הבוחר טכנולוגיות טיפול כשרשרת טכנולוגיות בהתאם לתנאים המכתיבים את ההרכבים המותרים של שלבי טיפול מסוימים, בהתאם לאיכות זרם הכניסה והדרישה לאיכות הזרם ביציאה, בהתאם לפרמטרים המאפיינים את איכות הקולחים (השפכים המטופלים). כאשר הפתרון המתקבל ממודל האופטימיזציה, הוא פתרון של שרשרת טכנולוגיות טיפול, המתקבלת במינימום עלות בהתאם לאילוצי פרמטרים האיכות, אילוצים פיזיקליים, תפעוליים וטכנולוגיים.

עבור בעיית האופטימיזציה של בחירת טכנולוגיות הטיפול, פיתחנו שני מודלים, מודל של חמישה שלבי טיפול ומודל ללא הגבלה של מספר שלבי טיפול. כאשר חמשת שלבי הטיפול הם: 1) טיפול קדם, 2) טיפול ראשוני, 3) טיפול שניוני, 4)טיפול שלישוני ו- 5) חיטוי. טכנולוגיית טיפול אחת נבחרת עבור כל שלב טיפול. לעומת זאת, המודל ללא הגבלה של שלבי הטיפול מתאר בחירת טכנולוגיות טיפול ללא כל הגבלה של שלבי טיפול, כלומר הבחירה של הטכנולוגיה מתבצעת ממשרעת של 44 טכנולוגיות הנמצאות בבסיס הנתונים של המודל.

כמוצר משני של העבודה הזו, ובהתבסס על החלק הראשון שתיארנו, בעיית האופטימיזציה לבחירת טכנולוגיות טיפול, פיתחנו מודל אזורי לתכנון מערך הטיפול בשפכים, הולכת השפכים והקולחים ומערך אגירה. המודל מתייחס לשתי בעיות, בעיית התכן ובעיית התפעול של הרשת הכוללת, מערכת הולכת השפכים מן המקור אל המכונים לטיפול בשפכים, מערכת הולכת הקולחים עד משתמש הקצה ומערך אגירה.

למודלים אלו ביצענו הרצות בסיס וניתוחי רגישות, על מנת לבדוק איך המודלים מגיבים לתרחישים השונים, לדוגמה, שינויים בדרישות איכות הקולחים המסופקים לצרכנים החקלאיים, ושינויים בעלות הנזק הסביבתי. התוצאות שקיבלנו מעידות, שהמודלים שפיתחנו בעבודה זו, יכולים להוות כלי עזר למקבלי ההחלטות, בנושאים הקשורים להשפעות ולנזק הנגרם כתוצאה משינויי באיכות הקולחים ביציאה מהמט״ש ועד הצרכן, ואיך זה בא לידי ביטוי בעיצוב בעיית התכן המתקבלת, דבר המאפשר תכנון אופטימלי למערך הקולחים וההקצאות תחת אילוצים פיזיקליים, טכנולוגים וסביבתיים שונים.

מערכת קבלת החלטות לתכנון אופטימלי של מערכות לטיפול בשפכים

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הפקולטה לניהול

החוג לניהול משאבי טבע וסביבה

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