SYNTHESIS AND DESIGN STRATEGIES FOR THE DEVELOPMENT OF MACROSCOPIC INTERPLANT WATER NETWORKS IN INDUSTRIAL ZONES

A Dissertation

by

SABLA ALNOURI

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Chair of Committee,	Patrick Linke
Co-Chair of Committee,	Mahmoud El-Halwagi
Committee Members,	James Holste
	Eyad Masad
Head of Department,	Nazmul Karim

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ABSTRACT

Increased water scarcity problems, coupled with the immense scale of water-intensive industrial activities in the region demands for the development of optimal water reuse and recycling strategies in industrial cities. Hence, industrial water and wastewater management is a key research priority. As a result, several necessary aspects that have not been addressed previously in water integration methods have been considered in this work, by developing and implementing a framework which allows for improved applications of macroscopic water integration in complex industrial regions. The main components relevant to the planning of cost-effective water networks in a devised city plan have been captured with a focus on identifying cost-effective water allocations within an industrial city.

Detailed information associated with water-using and water-consuming entities have been captured, using both flowrate and contamination information as well as site location information. Hence, a spatial representation that is capable of capturing an industrial city arrangement, has been developed to assist in water network design, an aspect which has often been overlooked in existing methods. Moreover, the presence of a number of different options during the selection process of appropriate treatment technologies, as well as the efficient placement of corresponding treatment facilities, have also been considered. In addition to the above aspects, two different pipeline merging representations that are capable of identifying cost-effective opportunities have also been captured in this work. Both approaches allow for the screening of less complex

pipeline networks, by assembling together commonly existing pipe sections, in the course of determining optimal water networks. All methods were implemented and demonstrated using several industrial city layout scenarios, and each method was able to identify a number of optimal synergies.

DEDICATION

To my parents, who taught me to learn from success and failure

ACKNOWLEDGEMENTS

I am truly grateful to everyone who has assisted me throughout this course of study. This has been one of the most fantastic periods in my life, and all the hard work, determination and perseverance that was eventually culminated by this dissertation would have never been possible without the guidance, encouragement and support that I have received.

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NOMENCLATURE

p	Plant/Process
i	Water Source
j	Water Sink
r	Treatment Interceptor Within Plant
s	Central Treatment Interceptor
l	Freshwater Type
t	Central Treatment Interceptor Type
c	Contaminant
A	First Level Node Associated with Pipeline Branching
B	Second Level Node Associated with Pipeline Branching
C	Third Level Node Associated with Pipeline Branching
N	N^{th} Level Node Associated with Pipeline Branching
$z_{cj,p}^{min}$	Minimum Permissible Pollutant c Composition in Sink j, Plant p (ppm)
$z_{c,jp}^{max}$	Maximum Permissible Pollutant c Composition in Sink j, Plant p (ppm)
G_{jp}	Flowrate Required in Sink j, Plant p (kg/h)
W_{ip}	Flowrate Available in Sink j, Plant p (kg/h)
$x_{c,ip}^{Source}$	Pollutant c Composition in Source i, Plant p (ppm)

$x_{c,l}^{FRESH}$	Pollutant c Composition in External Freshwater of Type *l* (ppm)
L	Lower Bound For Flow into a Treatment Unit (kg/h)
U	Upper Bound For Flow into a Treatment Unit (kg/h)
$RR_{c,rp}$	Removal Ratio of Pollutant c in treatment Interceptor r, Plant p
$RR_{c,st}$	Removal Ratio of Pollutant c in Central Treatment Interceptor s of Type t
x_c^{Max}	Maximum Permissible Discharge Concentration of Pollutant c
ε	Pipe Roughness
K_{ex}	Expansion Loss at Pipe Exit
K_c	Contraction Loss at Pipe Entrance
K_b	Loss At Pipe Elbow/Bend
ρ	Density (kg/m^3)
μ	Viscosity (kg/m s)
α	Coefficient Associated with Piping Cost Calculations
β	Power Coefficient Associated with Piping Cost Calculations
C^{WASTE}	Cost of Wastewater Discharge (\$/kg)
C_l^{FRESH}	Cost of Freshwater of Type l (\$/kg)
H_y	Operating Hours per Year (h/yr)
K_F	Treatment Annualized Factor (yr^{-1})
C_{rp}^{INV}	Treatment Within Plant p Unit Cost (\$)
C_{st}^{INV}	Central Treatment Type t Unit Cost (\$)

C_{rp}^{REM}	Treatment Within Plant p Mass Removed Cost ($/kg)
C_{st}^{REM}	Central Treatment Type T Mass Removed Cost ($/kg)
γ	Piping Cost Annualized Factor (yr^{-1})
η	Efficiency
P	Set of Plants/Processes in Industrial City
SU_p	Set of Water Sources In Plant p
SN_p	Set of Water Sinks In Plant p
R	Set of Decentralized Treatment Interceptors
S	Set of Central Treatment Interceptor Locations
T	Set of Central Treatment Interceptor Types
L	Set of Freshwater Types
C	Set of Contaminants/Pollutants
$X_{ip,jp'}$	Set of 1^{st} Level Nodes Associated With Stream Connecting Source i Plant p To Sink j Plant p' using either a Forward or Backward Branching Scenario
$Y_{ip,jp'}$	Set of 2^{nd} Level Nodes Associated With Stream Connecting Source i Plant p To Sink j Plant p' using either a Forward or Backward Branching Scenario
$Z_{ip,jp'}$	Set of 3^{rd} Level Nodes Associated With Stream Connecting Source i Plant p To Sink j Plant p' using either a Forward or Backward Branching Scenario

$N_{ip,jp'}$ Set of N^th Level Nodes Associated With Stream Connecting Source i Plant p To Sink j Plant p' using either a Forward or Backward Branching Scenario

X_{jp} Set of 1^st Level Nodes Associated with Stream Connecting Freshwater Mains to Sink j Plant p' using a Forward Branching Scenario

Y_{jp} Set of 2^nd Level Nodes Associated with Stream Connecting Freshwater Mains to Sink j Plant p' using a Forward Branching Scenario

Z_{jp} Set of 3^rd Level Nodes Associated with Stream Connecting Freshwater Mains to Sink j Plant p' using a Forward Branching Scenario

N_{jp} Set of N^th Level Nodes Associated with Stream Connecting Freshwater Mains to Sink j Plant p' using a Forward Branching Scenario

X_{ip} Set of 1^st Level Nodes Associated with Stream Connecting Source i Plant p to Wastewater Mains using a Backward Branching Scenario

Y_{ip} Set of 2^nd Level Nodes Associated with Stream Connecting Source i Plant p to Wastewater Mains using a Backward Branching Scenario

Z_{ip} — Set of 3rd Level Nodes Associated with Stream Connecting Source i Plant p to Wastewater Mains using a Backward Branching Scenario

N_{ip} — Set of Nth Level Nodes Associated with Stream Connecting Source i Plant p to Wastewater Mains using a Backward Branching Scenario

$X_{ip,rp}$ — Set of 1st Level Nodes Associated with Stream Connecting Source i Plant p To De-Central Treatment Facility R in the Same Plant p Using a Forward Branching Scenario

$Y_{ip,rp}$ — Set of 2nd Level Nodes Associated with Stream Connecting Source i Plant p To De-Central Treatment Facility R in the Same Plant p Using a Forward Branching Scenario

$Z_{ip,rp}$ — Set of 3rd Level Nodes Associated with Stream Connecting Source i Plant p To De-Central Treatment Facility R in the Same Plant p Using a Forward Branching Scenario

$N_{ip,rp}$ — Set of Nth Level Nodes Associated with Stream Connecting Source i Plant p To De-Central Treatment Facility R in the Same Plant p Using a Forward Branching Scenario

$X_{ip,st}$ — Set of 1st Level Nodes Associated with Stream Connecting Source i Plant p to a Central Treatment Facility of Type t using a Forward Branching Scenario

$Y_{ip,st}$ Set of 2nd Level Nodes Associated with Stream Connecting Source i Plant p to a Central Treatment Facility of Type t using a Forward Branching Scenario

$Z_{ip,st}$ Set of 3rd Level Nodes Associated with Stream Connecting Source i Plant p to a Central Treatment Facility of Type t using a Forward Branching Scenario

$N_{ip,st}$ Set of Nth Level Nodes Associated with Stream Connecting Source i Plant p to a Central Treatment Facility of Type t using a Forward Branching Scenario

$X_{rp,jp'}$ Set of 1st Level Nodes Associated with Stream Connecting De-Central Treatment Facility r In Plant p to Sink j in Plant p' using a Backward Branching Scenario

$Y_{rp,jp'}$ Set of 2nd Level Nodes Associated with Stream Connecting De-Central Treatment Facility r In Plant p to Sink j in Plant p' using a Backward Branching Scenario

$Z_{rp,jp'}$ Set of 3rd Level Nodes Associated with Stream Connecting De-Central Treatment Facility r In Plant p to Sink j in Plant p' using a Backward Branching Scenario

$N_{rp,jp'}$ Set of Nth Level Nodes Associated with Stream Connecting De-Central Treatment Facility r In Plant p to Sink j in Plant p' using a Backward Branching Scenario

$X_{st,jp}$	Set of 1st Level Nodes Associated with Stream Connecting Central Treatment Facility S of Type t to Sink j in Plant p using a Backward Branching Scenario
$Y_{st,jp}$	Set of 2nd Level Nodes Associated with Stream Connecting Central Treatment Facility S of Type t to Sink j in Plant p using a Backward Branching Scenario
$Z_{st,jp}$	Set of 3er Level Nodes Associated with Stream Connecting Central Treatment Facility S of Type t to Sink j in Plant p using a Branching Scenario
$N_{st,jp}$	Set of Nth Level Nodes Associated with Stream Connecting Central Treatment Facility S of Type t to Sink j in Plant p using a Backward Branching Scenario
X_{rp}	Set of 1st Level Nodes Associated with Stream Connecting De-Central Treatment Facility r on Plant p to Wastewater Mains using a Backward Branching Scenario
Y_{rp}	Set of 2nd Level Nodes Associated with Stream Connecting De-Central Treatment Facility r on Plant p to Wastewater Mains using a Backward Branching Scenario
Z_{rp}	Set of 3rd Level Nodes Associated with Stream Connecting De-Central Treatment Facility r on Plant p to Wastewater Mains using a Backward Branching Scenario

N_{rp} Set of Nth Level Nodes Associated with Stream Connecting De-Central Treatment Facility r on Plant p to Wastewater Mains using a Backward Branching Scenario

X_{st} Set of 1st Level Nodes Associated with Stream Connecting Central Treatment Facility s of Type t to Wastewater Mains using a Backward Branching Scenario

Y_{st} Set of 2nd Level Nodes Associated with Stream Connecting Central Treatment Facility s of Type t to Wastewater Mains using a Backward Branching Scenario

Z_{st} Set of 3rd Level Nodes Associated with Stream Connecting Central Treatment Facility s of Type t to Wastewater Mains using a Backward Branching Scenario

N_{st} Set of Nth Level Nodes Associated with Stream Connecting Central Treatment Facility s of Type t to Wastewater Mains using a Backward Branching Scenario

FC Total Freshwater Costs ($)

TC Total Central and De-Central Treatment Costs ($)

PC Total Piping Costs ($)

WC Total Wastewater Discharge Costs ($)

$z_{c,jp}^{in}$ Pollutant c Composition in Sink j, Plant p (ppm)

$M_{ip,jp'}$ Mass Flowrate from Source i, Plant p to Sink j, Plant p' (kg/h)

$F_{l,jp}$	External Freshwater Mass Flowrate of Type l Required in Sink j, Plant p (kg/h)
D_{ip}	Wastewater Mass Flowrate Discharged by Source i, Plant p (kg/h)
$T_{ip,rp}$	Mass Flowrate From Source i, Plant P to Interceptor r Plant p (kg/h)
$T_{ip,st}$	Mass Flowrate from Source i, Plant p to Interceptor s of Type t (kg/h)
$T_{rp,jp}$	Mass Flowrate From Interceptor r Plant p to Sink j, Plant p (kg/h)
$T_{st,jp}$	mass flowrate from interceptor s of type to sink j, plant p (kg/h)
D_{rp}	Wastewater Mass Flowrate Discharged by Interceptor r, Plant p (kg/h)
D_{st}	Wastewater Mass Flowrate Discharged by Central Interceptor s of Type t (kg/h)
T_{rp}^{total}	Total Mass Flowrate into Interceptor r, Plant p (kg/h)
T_{st}^{total}	Total Mass Flowrate into Central Interceptor s of Type t (kg/h)
D^{total}	Total Wastewater Discharged (kg/h)
$x_{c,rp}^{in}$	Inlet Concentration of Contaminant c into Interceptor r, Plant p (ppm)
y_{st}	Binary Variable Associated with the Selection of Treatment Type t, In a Centralized Treatment Location s
y_k	Binary Variable Associated with Discrete Diameter di_k

$x_{c,rp}^{out}$ Outlet Concentration of Contaminant c into Interceptor r, Plant p (ppm)

$x_{c,st}^{REM}$ Total Mass Removed of Contaminant c in Interceptor r, Plant p (ppm)

$x_{c,st}^{in}$ Inlet Concentration Of Contaminant c Into Central Interceptor S of Type t (ppm)

$x_{c,st}^{out}$ Outlet Concentration of Contaminant C into Central Interceptor S of Type t (ppm)

$x_{c,st}^{REM}$ Total Mass Removed Contaminant c in Central Interceptor S of Type t (ppm)

$x_{c}^{Discharge}$ Total Discharge Concentration of Contaminant c

$L_{ip\,jp'}$ Length of Pipe from Source i, Plant p to Sink j Plant p' (m)

L_{ip} Length of Pipe Carrying Unused Wastewater from Source i, Plant p to Mainstream Waste (m)

$L_{l,jp}$ Length of Pipe Carrying Type l Freshwater from Mainstream to Sink j, Plant p (m)

$L_{ip,rp}$ Length of Pipe from Source i, Plant p to Interceptor r Plant p (m)

$L_{ip,st}$ Length of Pipe from Source i, Plant p to Interceptor s of Type t (m)

$L_{rp,jp}$ Length of Pipe from Interceptor r Plant p to Sink j, Plant p (m)

$L_{st,jp}$ Length of Pipe from Interceptor s of Type to Sink j, Plant p (m)

L_{rp}	Length of Pipe Carrying Unused Wastewater from Interceptor r, Plant p to Mainstream Waste (m)
L_{st}	Length of Pipe Carrying Unused Wastewater from central Interceptor s, Type t to Mainstream Waste (m)
$L_{ip\,jp'}^{a}$	Length of Pipe Segment up to the 1st Level Node a, Carrying water from Source i, Plant p to Sink j Plant p'
$L\,_{ip}^{a}$	Length of Pipe Segment up to 1st Level Node a, Carrying Wastewater from Source i, Plant p to the Waste Mainstream
$L\,_{jp}^{a}$	Length of Pipe Segment up to 1st Level Node a, Carrying Freshwater from Mainstream to Sink j, Plant p
$L_{ip\,jp'}^{a,b}$	Length of Pipe Segment from 1st Level Node a to 2nd Level Node b, Carrying water from Source i, Plant p to Sink j Plant p'
$L\,_{ip}^{a,b}$	Length of Pipe Segment from 1st Level Node a to 2nd Level Node b, Carrying Wastewater from Source i, Plant p to the Waste Mainstream
$L\,_{jp}^{a,b}$	Length of Pipe Segment from 1st Level Node a to 2nd Level Node b, Carrying Freshwater from Mainstream to Sink j, Plant p
$L_{ip\,jp'}^{a,b,c}$	Length of Pipe Segment from 2nd Level Node b to 3rd Level Node c, Carrying water from Source i, Plant p to Sink j Plant p' through 1st Level Node a

$L_{ip}^{a,b,c}$	Length of Pipe Segment from 2nd Level Node b to 3rd Level Node c, Carrying Wastewater from Source i, Plant p to the Waste Mainstream through 1st Level Node a
$L_{jp}^{a,b,c}$	Length of Pipe Segment from 2nd Level Node b to 3rd Level Node c, Carrying Freshwater from Mainstream to Sink j, Plant p through 1st Level Node a
$L_{ip\,jp'}^{a,b,c,..,n-1,n}$	Length of Pipe Segment from (n-1)th Level Node (n-1) to nth level node n, Carrying water from Source i, Plant p to Sink j Plant p' through nodes a, b and c onwards
$L_{ip}^{a,b,c,..,n-1,n}$	Length of Pipe Segment from (n-1)th Level Node (n-1) to nth level node n, Carrying Wastewater from Source i, Plant p to the Waste Mainstream through nodes a, b and c onwards
$L_{jp}^{a,b,c,..,n-1,n}$	Length of Pipe Segment from node (n-1)th Level Node (n-1) to nth Level Node n, Carrying Freshwater from Mainstream to Sink j, Plant p through nodes a, b and c onwards
$DI_{ip,jp'}$	Calculated Diameter of Pipe from Source i, Plant p to Sink j Plant p' (m)
DI_{ip}	Calculated Diameter of Pipe Carrying unused Wastewater from Source i, Plant p to Mainstream Waste (m)
$DI_{l,jp}$	Calculated Diameter of Pipe Carrying Type l Freshwater from Mainstream to Sink j, Plant p (m)

$DI_{ip,rp}$	Calculated Diameter of Pipe from Source i, Plant p to Interceptor r Plant p (m)
$DI_{ip,st}$ s	Calculated Diameter of Pipe from Source i, Plant p to Interceptor of Type t (m)
$DI_{rp,jp}$	Calculated Diameter of Pipe from Interceptor r, Plant p to Sink j, Plant p (m)
$DI_{st,jp}$	Calculated Diameter of Pipe from Central Interceptor s of Type t to Sink j, Plant p (m)
DI_{rp}	Calculated Diameter of Pipe Carrying unused Wastewater from Interceptor r, Plant p to Mainstream Waste (m)
DI_{st}	Calculated Diameter of Pipe Carrying unused Wastewater from Central Interceptor s, Type t to Mainstream Waste (m)
$M_{ip\,jp'}^{a}$	Flowrate in Pipe Segment up to the 1st Level Node a, Carrying Water from Source i, Plant p to Sink j Plant p'
D_{ip}^{a}	Flowrate in Pipe Segment up to 1st Level Node a, Carrying Wastewater from Source i, Plant p to the Waste Mainstream
F_{jp}^{a}	Flowrate in Pipe Segment up to 1st Level Node a, Carrying Freshwater from Mainstream to Sink j, Plant p
$M_{ip\,jp'}^{a,b}$	Flowrate in Pipe Segment from 1st Level Node a to 2nd Level Node b, Carrying Water from Source i, Plant p to Sink j Plant p'

$D_{ip}^{a,b}$	Flowrate in Pipe Segment from 1st Level Node a to 2nd Level Node b, Carrying Wastewater from Source i, Plant p to the Waste Mainstream
$F_{jp}^{a,b}$	Flowrate in Pipe Segment from 1st Level Node a to 2nd Level Node b, Carrying Freshwater from Mainstream to Sink j, Plant p
$M_{ipjp'}^{a,b,c}$	Flowrate in Pipe Segment from 2nd Level Node b to 3rd Level Node c, Carrying Water from Source i, Plant p to Sink j Plant p' through 1st Level Node a
$D_{ip}^{a,b,c}$	Flowrate in Pipe Segment from 2nd Level Node b to 3rd Level Node c, Carrying Wastewater from Source i, Plant p to the Waste Mainstream through 1st Level Node a
$F_{jp}^{a,b,c}$	Flowrate in Pipe Segment from 2nd Level Node b to 3rd Level Node c, Carrying Freshwater from Mainstream to Sink j, Plant p through 1st Level Node a
$M_{ipjp'}^{a,b,c,..,n-1,n}$	Flowrate in Pipe Segment from (n-1)th Level Node (n-1) to nth Level Node n, Carrying Water from Source i, Plant p to Sink j Plant p' through Nodes a, b and c Onwards
$D_{ip}^{a,b,c,..,n-1,n}$	Flowrate in Pipe Segment from (n-1)th Level Node (n-1) to nth Level Node n, Carrying Wastewater from Source i, Plant p to the Waste Mainstream through Nodes a, b and c Onwards

$F_{jp}^{a,b,c,..,n-1,n}$ Flowrate in Pipe Segment from node (n-1)th Level Node (n-1) to Nth Level Node n, carrying Freshwater from Mainstream to Sink j, Plant p through Nodes a, b and c Onwards

$T_{ip,rp}^{a}$ Flowrate in Pipe Segment up to the 1st Level Node a, Carrying Water from Source i, Plant p to De-Centralized Treatment Unit r in Plant p

$T_{ip,st}^{a}$ Flowrate in Pipe Segment up to the 1st Level Node a, Carrying Water from Source i, Plant p to Centralized Treatment Unit s of Type t

$T_{rp,jp\prime}^{a}$ Flowrate in Pipe Segment up to the 1st Level Node a, Carrying Water from De-Centralized Treatment Unit r in Plant p to Sink j Plant p'

$T_{st,jp\prime}^{a}$ Flowrate in Pipe Segment up to the 1st Level Node a, Carrying Water from Centralized Treatment Unit s of Type t to Sink j Plant p'

D_{rp}^{a} Flowrate in Pipe Segment from 1st Level Node a to 2nd Level Node b Carrying Wastewater from De-Centralized Treatment Unit r in Plant p to the Waste Mainstream

D_{st}^{a} Flowrate in Pipe Segment from 1st Level Node a to 2nd Level Node b Carrying Wastewater from Centralized Treatment Unit s of Type t to the Waste Mainstream

$T_{ip,rp}^{a,b}$	Flowrate in Pipe Segment from 1st Level Node a to 2nd Level Node b, Carrying Water from Source i, Plant p to De-Centralized Treatment Unit r in Plant p
$T_{ip,st}^{a,b}$	Flowrate in Pipe Segment from 1st Level Node a to 2nd Level Node b, Carrying Water from Source i, Plant p to Centralized Treatment Unit s of Type t
$T_{rp,jp'}^{a,b}$	Flowrate in Pipe Segment from 1st Level Node a to 2nd Level Node b, Carrying Water from De-Centralized Treatment Unit r in Plant p to Sink j Plant p'
$T_{st,jp'}^{a,b}$	Flowrate in Pipe Segment from 1st Level Node a to 2nd Level Node b, Carrying Water from Centralized Treatment Unit s of Type t to Sink j Plant p'
$D_{rp}^{a,b,c}$	Flowrate in Pipe Segment from 1st Level Node a to 2nd Level Node b, Carrying Wastewater from De-Centralized Treatment Unit r in Plant p to the Waste Mainstream
$D_{st}^{a,b,c}$	Flowrate in Pipe Segment from 1st Level Node a to 2nd Level Node b, Carrying Wastewater from Centralized Treatment Unit s of Type t to the Waste Mainstream
$T_{ip,rp}^{a,b,c}$	Flowrate in Pipe Segment from 2nd Level Node b to 3rd Level Node c, Carrying Water from Source i, Plant p to De-Centralized Treatment Unit r in Plant p

$T_{ip,st}^{a,b,c}$ Flowrate in Pipe Segment from 2nd Level Node b to 3rd Level Node c, Carrying Water from Source i, Plant p to Centralized Treatment Unit s of Type t

$T_{rp,jp'}^{a,b,c}$ Flowrate in Pipe Segment from 2nd Level Node b to 3rd Level Node c, Carrying Water from De-Centralized Treatment Unit r in Plant p to Sink j Plant p'

$T_{st,jp'}^{a,b,c}$ Flowrate in Pipe Segment from 2nd Level Node b to 3rd Level Node c, Carrying Water from Centralized Treatment Unit s of Type t to Sink j Plant p'

$D_{rp}^{a,b,c}$ Flowrate in Pipe Segment from 2nd Level Node b to 3rd Level Node c, Carrying Wastewater from De-Centralized Treatment Unit r in Plant p to the Waste Mainstream

$D_{st}^{a,b,c}$ Flowrate in Pipe Segment from 2nd Level Node b to 3rd Level Node c, Carrying Wastewater from Centralized Treatment Unit s of Type t to the Waste Mainstream

$T_{ip,rp}^{a,b,c,..,n-1,n}$ Flowrate in Pipe Segment from node (n-1)th Level Node (n-1) to Nth Level Node n, Carrying Water from Source i, Plant p to De-Centralized Treatment Unit r in Plant p

$T_{ip,st}^{a,b,c,..,n-1,n}$ Flowrate in Pipe Segment from node (n-1)th Level Node (n-1) to Nth Level Node n, Carrying Water from Source i, Plant p to Centralized Treatment Unit s of Type t

$T_{rp,jp'}^{a,b,c,..,n-1,n}$ Flowrate in Pipe Segment from node (n-1)th Level Node (n-1) to Nth Level Node n, Carrying Water from De-Centralized Treatment Unit r in Plant p to Sink j Plant p'

$T_{st,jp'}^{a,b,c,..,n-1,n}$ Flowrate in Pipe Segment from node (n-1)th Level Node (n-1) to Nth Level Node n, Carrying Water from Centralized Treatment Unit s of Type t to Sink j Plant p'

$D_{rp}^{a,b,c,..,n-1,n}$ Flowrate in Pipe Segment from node (n-1)th Level Node (n-1) to Nth Level Node n, Carrying Wastewater from De-Centralized Treatment Unit r in Plant p to the Waste Mainstream

$D_{st}^{a,b,c,..,n-1,n}$ Flowrate in Pipe Segment from node (n-1)th Level Node (n-1) to Nth Level Node n, Carrying Wastewater from Centralized Treatment Unit s of Type t to the Waste Mainstream

$DI_{ipjp'}^{a}$ Diameter of Pipe Segment up to the 1st Level Node a, Carrying Water from Source i, Plant p to Sink j Plant p'

DI_{ip}^{a} Diameter of Pipe Segment up to 1st Level Node a, Carrying Wastewater from Source i, Plant p to the Waste Mainstream

DI_{jp}^{a} Diameter of Pipe Segment up to 1st Level Node a, Carrying Freshwater from Mainstream to Sink j, Plant p

$DI_{ipjp'}^{a,b}$ Diameter of Pipe Segment from 1st Level Node a to 2nd Level Node b, Carrying Water from Source i, Plant p to Sink j Plant p'

$DI_{ip}^{a,b}$ Diameter of Pipe Segment from 1st Level Node a to 2nd Level Node b Carrying Wastewater from Source i, Plant p to the Waste Mainstream

$DI_{jp}^{a,b}$ Diameter of Pipe Segment from 1st Level Node a to 2nd Level Node b Carrying Freshwater from Mainstream to Sink j, Plant p

$DI_{ip\,jp'}^{a,b,c}$ Diameter of Pipe Segment from 2nd Level Node b to 3rd Level Node c, Carrying Water from Source i, Plant p to Sink j Plant p' through 1st Level Node a

$DI\ _{ip}^{a,b,c}$ Diameter of Pipe Segment from 2nd Level Node b to 3rd Level Node c, carrying Wastewater from Source i, Plant p to the waste Mainstream through 1st Level Node a

$DI\ _{jp}^{a,b,c}$ Diameter of Pipe Segment from 2nd Level Node b to 3rd Level Node c, Carrying Freshwater from Mainstream to Sink j, Plant p through 1st Level Node a

$DI_{ip\,jp'}^{a,b,c,..,n-1,n}$ Diameter of Pipe Segment from (n-1)th Level Node (n-1) to nth Level Node n, Carrying Water from Source i, Plant p to Sink j Plant p' through Nodes a, b and c Onwards

$DI\ _{ip}^{a,b,c,..,n-1,n}$ Diameter of Pipe Segment from (n-1)th Level Node (n-1) to nth level node n, Carrying Wastewater from Source i, Plant p to the Waste Mainstream through Nodes a, b and c Onwards

$DI_{jp}^{a,b,c,..,n-1,n}$	Diameter of Pipe Segment from node (n-1)th Level Node (n-1) to nth Level Node n, Carrying Freshwater from Mainstream to Sink j, Plant p through nodes a, b and c Onwards
N^E	Number of Elbows/Bends in Pipe
N_{Re}	Reynolds's Number of Water Stream
v	Velocity (m/s)
f	Fanning Friction Factor
A	Parameter Based on Churchill's Equation for Fanning Friction Factor Calculations
ΔF^f	Friction Losses
ΔP^{Drop}	Pressure Drop due to Friction
P^w	Shaft Power Required to Overcome Pressure Drop
$f_{ip,rp}$	Split Fraction of Stream from Source i Plant P to Decentral Treatment Plant r in the Same Plant p
$f_{ip,st}$	Split Fraction of Stream From Source i Plant p to Central Treatment Plant s of Type t
K	Number of Discrete Diameter Values

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

Industrial water and wastewater management is a research priority in many regions, due to the global increase in various water-intensive industrial activities. Wastewater reuse certainly alleviates the depletion of available freshwater sources that are present around industrial areas. Wastewater reuse also helps reduce the excessive waste quantities being discharged into natural water bodies. Many industrial sites that lie in proximity to coastal areas involve large volumes of unused wastewater being diverted back into the sea, which negatively impacts aquatic life. Identifying appropriate wastewater treatment alternatives is also of significant importance due to the stringent discharge limits being imposed on industrial wastewater, as well as the strict effluent standards that industries are expected to adhere to. Potential opportunities for industrial wastewater reuse would absolutely vary from one industry to another, depending on a number of important factors such as the quantity and quality of wastewater produced.

Therefore, one of the main aspects of this research is the development of an effective methodology that assists in determining efficient wastewater reuse practices in accordance to produced wastewater qualities, within industrial sites. The concept of an eco-industrial park (EIP) has also been utilized in this context, for the integration of on-site water resources. For instance, several wastewater-producing operations that exist within a number of industrial facilities can be identified as appropriate to partially or exclusively satisfy a number of coexisting water-consuming operations, by matching their corresponding flows and water qualities. Moreover, wastewater treatment opportunities can also be introduced whenever found necessary. Several different options for the selection of appropriate treatment technologies, as well as the efficient placement of corresponding treatment facilities, have also been incorporated as follows: (1) the possibility of a cluster of processing establishments sharing a common treatment facility (centralized), (2) the possibility of placing a treatment facility as an individual entity that belongs to a particular industrial site (decentralized).

Moreover, the main components relevant to the effective planning and design of macroscopic water networks have been captured in this work with a focus on the following aspects: (1) existing processing facilities, water consumption and wastewater production capacities, (2) site locations and the spatial distribution of all site entities that entail water use or production, and (3) common infrastructure boundaries, such as the existence of industrial corridors that can be utilized for water transportation. A structured representation has been developed to effectively capture the spatial elements of the problem. Hence, the proposed framework unifies water integration and network design approaches by identifying and exploiting optimal synergies for wastewater minimization and reuse across several processes within an industrial complex. Moreover, the methodology allows cost-effective interplant water reuse and treatment network designs to be identified, by implementing a systematic approach for interplant water network synthesis and design. Additional considerations that account for pipe merging scenarios have also been incorporated.

CHAPTER II

WATER INTEGRATION IN INDUSTRIAL ZONES: A SPATIAL REPRESENTATION WITH DIRECT RECYCLE APPLICATIONS*

This work introduces a representation of spatial aspects in water integration problems within industrial zones, which can be applied to problems involving any type of water integration strategies. The representation is flexible and takes into consideration the respective plant locations, and any barriers that exist in between. Moreover, industrial city corridors that are allocated for water transport have also been accounted for. This allows effective water integration and matching amongst available water streams using a spatially constrained approach that utilizes the shortest path options available. The proposed representation has been illustrated using direct recycling integration strategies, which in turn are commonly recognized to employ the simplest techniques for water integration, as a first instance. A case study involving several water using and producing processes that belong to a group of plants all operating in a common industrial zone has been carried out as a demonstration, and several different scenarios have been studied. In doing so, cost effective water network designs that involve attractive wastewater reuse schemes amongst adjacent and nearby processing facilities have been identified, while considering the spatial constraints of water transport.

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II.1. Introduction

The use of water is essential in numerous industrial applications. However, freshwater is turning into a scarce and valuable resource as a result of the rapid growth in global water consumption. Moreover, wastewater streams have turned into a predicament in many industrial processes, as a result of the increasingly stringent environmental regulations pertaining to its discharge. Due to potential saving opportunities foreseen as a result of wastewater reuse that can partially replace freshwater consumption, the concept of wastewater treatment, recycling and re-use in processing facilities has received considerable attention throughout the past four decades. Generally speaking, previous work that involves wastewater reuse outlooks dates back to the 1970's (Carnes, Ford et al. 1973; Hospondarec and Thompson 1974; Skylov and Stenzel 1974; Sane and Atkins 1977),in which attempts that involve treatment and reuse of wastewaters within freshwater-consuming processes have been considered. Additionally, specific water management theories, schemes and concepts have been discussed. As of today, efforts directed towards the design and retrofit of water networks that consider wastewater treatment, recycling and distribution are being successfully implemented in numerous processes through the application of existing water integration methodologies.

II.2. Literature Review

II.2.1 Local Water Integration Methods

The application of mathematical and computer aided optimization techniques for the design of wastewater treatment systems has been applied in previous water integration studies. (Mishra, Fan et al. 1975; Takama, Kuriyama et al. 1980). For instance, Takama et al. (1980) relied on the use of mathematical programming tools to optimize a superstructure for the distribution of water streams in a petroleum refinery. Eliminating irrelevant and uneconomical connections from the superstructure helped condense the problem, and thus limit the number of water allocation options available within the process.

By the end of the 1980's, the concept of synthesizing mass exchanger networks (MENs), as well as the development of systematic tools for their optimal design was introduced and applied by El-Halwagi and Manousiouthakis (1989a; 1989b, 1990a, 1990b) which involves an analogous philosophy that is used for creating heat exchanger (Linnhoff and Flower 1978; Linnhoff and Hindmarsh 1983). The idea of obtaining the cumulative mass exchanged in relation to contaminant composition for a set of rich and lean streams, then applying a pinch analysis to enable the identification of rigorous targets for Mass Separating Agents (MSAs) for a single component, as well as economical MEN solutions using the same targets. The work was then extended to incorporate multicomponent targets (El-Halwagi and Manousiouthakis 1989b), as well as the integration of regeneration networks within MEN designs (El-Halwagi and Manousiouthakis 1990b). Wang and Smith (1994a, 1994b) proposed a theoretical methodology that is aimed towards maximizing water reuse in process industries for both single and multiple contaminants, in which constraints such as minimum mass transfer driving force, fouling and corrosion limitations can be specified. Moreover, water regeneration opportunities were also identified via a targeting stage.

Since then many subsequent developments for water targeting and maximum water reuse have been attempted. For instance, Dhole et al. (1996) presented a targeting approach for networks that involve fixed flowrate operations. Studies that account for water effluent treatment, as well as interactions between water reuse and wastewater treatment were also conducted (Kuo and Smith 1997; Kuo and Smith 1998). Doyle and Smith (1997) presented a superstructure optimization approach for targeting water reuse in which multiple contaminants are involved, and a special iterative procedure is used to solve the problem. Olesen and Polley (1997) developed a procedure for water network design involving simple direct water re-use, water draw-off, and regenerated water re-use. Alva-Argáez et al. (1998) introduced a decomposition scheme that utilizes a recursive technique, for a superstructure optimization model that includes all the possible features of a water network design. A network featuring minimum total annualized cost can be found where the complexity of the network structure is under the control of the designer. Savelski and Bagajewicz (2000) investigated the necessary conditions associated with optimal water allocation planning (WAP) problems, as well as consider wastewater reuse by minimizing the total water intake based on a single contaminant. Hallale (2002) introduced a graphical method for obtaining freshwater and wastewater targets by constructing water surplus diagrams, that are analogous to the grand composite curves utilized in heat integration pinch studies. El-Halwagi et al. (2003) presented a rigorous graphical targeting approach that minimizes freshwater consumption by means of direct recycling schemes using mixing and segregation principles. Manan et al. (2004) estimated the minimum water target using the water cascade analysis (WCA) technique, which is a numerical alternative to the graphical water targeting technique and can quickly yield an accurate estimate of the minimum water target, the pinch-point locations, and the water allocation target for maximum water recovery. Almutlaq et al. (2007) developed a systematic non-iterative algebraic approach that identifies rigorous targets for minimum usage of impure fresh resources, and minimum discharge of waste by identifying these targets without any obligations to the design details of the water allocation network. Prakash and Shenoy (2005) adopted a methodology that utilizes the nearest-neighbor principle to design networks with a minimized consumption of freshwater for fixed contaminant load, and fixed flow rate scenarios. Moreover, there exist many other contributions addressing water reuse that Foo (2009) subsequently detailed in a review paper.

Later and more recent studies concerning Water Allocation Problems (WAPs) have also been made, due to the growing interest for achieving sustainability within industries. De Faria et al. (2009) developed a non-linear program (NLP) model targeting the minimization of freshwater consumption and/or operating costs. The solutions were achieved using a two-step procedure in which the cost was optimized while fixing a previously obtained minimum freshwater consumption target. Poplewski et al. (2010) utilized a mixed-integer linear programming (MILP) model for a water network superstructure that could account for the presence of multiple contaminants. The study applied certain extensions to the standard formulation by enabling the exploration of various performance indices, as well as imposing conditions on continuous variables and network topology. In all methods that have been detailed above, much of the focus has been on a local level, i.e. within a single operating industrial facility.

II.2.2 Global (Inter-Plant) Water Integration Methods

Larger-scale problems that involve water integration across multiple operating facilities were then attempted, in which very similar principles that have been applied on a local water integration level were also utilized. Such problems are often referred to as Interplant Water Integration (IPWI) problems, as described by Chew et al. (2008). In the long run, achieving effective water integration amongst multiple coexisting plants would eventually call for the establishment of a setting that resembles an Eco-Industrial Park (EIP), which involves a cluster of several industrial processes operating in harmony(Côté and Hall 1995; Côté and Cohen-Rosenthal 1998). The processes need not be part of the same establishment or organization, but would usually share certain common resources or infrastructure facilities. EIP's are primarily designed in a way that would induce various integration options for water, energy and other materials. The participation of multiple facilities would need to offer attractive economic advantages over having stand-alone un-integrated processes running simultaneously (Gertler 1995).

EIP problems for managing industrial water were attempted previously in some studies, and were solved using a variety of mathematical programming techniques: NLP

(NonLinear Programming), MILP (Mixed-Integer linear Programming), and MINLP (Mixed-Integer NonLinear programming). Chew et al. (2008) studied the various opportunities for Interplant Water Integration (IPWI) problems, and both MILP and MINLP models were formulated to obtain global solutions for direct and indirect integration scenarios. Liao et al. (2007) investigate the design of flexible multiple plant water networks in terms of operating flexibility and cost, and combines both pinch techniques and mathematical programming. The number of cross plant interconnections was an important parameter in the water minimization problem. A MILP model was proposed for the design of flexible water networks of individual plants, which can be applied to fixed contaminant and fixed flow operations, while being limited to a single contaminant. Lovelady and El-Halwagi (2009) developed an optimization-based approach for water allocation amongst multiple processes in a common EIP facility. A source-interception-sink structural representation was used to embed all potential configurations, by accounting for direct recycling, as well as options for water treatment in interception units. Lim and Park (2009) reported a nonlinear programming method that remodeled a conventional industrial park as a green eco-industrial park, in which the objective function was to minimize the total consumption of industrial water. Aviso et al. (2010a, 2010b) presented models for optimizing water and wastewater reuse amongst several independent plants within an eco-industrial park setting. Moreover, identifying optimal network designs which were able to satisfy the objectives of participating plants were handled through fuzzy mathematical programming (Aviso, Tan et al. 2010a). Kim et al. (2010) introduced a systematic approach to optimize the utility network of an industrial complex with both economic and environmental considerations. The proposed approach consisted of unit modeling using thermodynamic principles, mass and energy balances, as well as the development of a multi-period Mixed Integer Linear Programming (MILP) model for the integration of utility systems in an industrial complex. Later on, Chew et al. (2010a, 2010b) utilized a new algorithm for targeting minimum freshwater use and waste discharges for an interplant resource conservation network (IPRCN). Taskhiri et al. (2011) presents a mixed-integer linear programming (MILP) model for interplant water network synthesis that involves minimizes the emergy of the network, by accounting for environmental impacts of water use, energy consumption, and capital goods within an EIP setting. Rubio-Castro et al. (2011) studied water integration in eco-industrial parks, using a superstructure representation that accounts for wastewater reuse both within the plant, as well as amongst different plants. A global optimal formulation was utilized to solve the problem. Later on, Rubio-Castro et al. (2012) examined ways to retrofit existing water networks from different plants within the same industrial zone, by accounting for both intra-plant and inter-plant structural modifications, using a MINLP model. Boix et al. (2012) utilized an MILP formulation for designing an Eco-Industrial Park (EIP) for three different EIP regeneration scenarios, based on the necessary conditions of optimality defined by Savelski and Bagajewicz (2000). More recently, Lee et al. (2013a) developed a two-stage optimization approach for inter-plant water network synthesis, for processing units that operate in a mix of both continuous and batch modes.

One of the major shortcomings of applying the existing methodologies is the inability to effectively capture industrial city layouts by locating the various plant arrangements, as well as any barriers and obstacles that affect water transport. Moreover, industrial cities have defined infrastructure boundaries that are available for water transport, more commonly known as service corridors. Due to the problem dependence on the layout of the industrial zone being investigated, accounting for the spatial aspects of the industrial zone provides the necessary information that can allow effective planning and structuring of piping and connectivity amongst the various plants. Even though most of the studies describe the problem as a water minimization problem, piping costs were considered an important aspect that needs to be appropriately addressed for designing cost effective interplant water networks. Previous studies that do account for piping in their objective function (Rubio-Castro, Ponce-Ortega et al. 2011; Boix, Montastruc et al. 2012), often rely on simplifying computations associated with pipe costing usually by assuming piping segments to be equal in length, or associated with a constant parameter that would reflect either intra presence (within a single plant) or inter presence (amongst several neighboring plants). Moreover, pressure drops in pipe segments are often disregarded, since they greatly depend on how the piping is structured. As a result, accounting for spatial constraints for water transport is inevitably essential. This work will address such limitations that have been reported, in an attempt to demonstrate the application of water allocation problems within industrial cities from a slightly different context.

II.3. Water Integration Framework

It has been shown that freshwater use, as well as wastewater generation can be minimized through the application of conventional targeting and direct recycle techniques. As mentioned in the introduction of this paper, there exist common methods and practices for water integration through direct recycling that have been developed over the past 20 years. Such methods would naturally require a fundamental understanding of the global water flow in a typical process for effective identification of performance targets. Generally speaking, the design objective in water-using networks is to minimize freshwater consumption by maximizing water reuse. Smith (2005) discusses several water system design scenarios for water integration: (1) water re-use, (2) regeneration re-use, and (3) regeneration recycling. All water system designs go from a linear scenario, which would naturally involve freshwater being is used in all operations, to a more effective circular design for which freshwater consumption is reduced through process water recycling. Introducing regeneration units that can reduce the amount of contaminants present in wastewater as indicated in the second and third scenarios can permit additional recycling of process water, especially highly contaminated streams. This could help achieve further reductions in external freshwater utilization, even though additional water treatment expenditures are involved.

Similarly, and in the context of macroscopic water reuse, Chew et al. (2008) described two different schemes for interplant water integration (1) a direct integration scheme in which water sources are directly integrated with water sinks existent within different plants, and (2) an indirect integration scheme that involves the utilization of a centralized system for utilities amongst all plants. Figure 1 (a) & (b) illustrate the existing direct water recycling concept discussed by Smith(2005), on a local level. Figure 1 (c) & (d) illustrate an analogy of the same concept from a macroscopic ‘direct integration’ perspective. Therefore, in an attempt to expand the scope of water integration problems, this paper focuses on the optimal spatial allocation of water streams amongst various water-using and wastewater producing facilities in multiple plant facilities, so as to achieve attractive matching of water streams within an industrial zone. The devised approach involves the application of direct recycling as the sole water integration strategy for a first instance, as an illustration, since it offers the simplest techniques for water integration. However, the proposed methodology can be applied to more complex problems involving any form of water integration, while simultaneously addressing the spatial aspects of the problem, while seeking potential opportunities for wastewater re-use amongst multiple processing facilities all existing and running simultaneously in a given industrial city region.

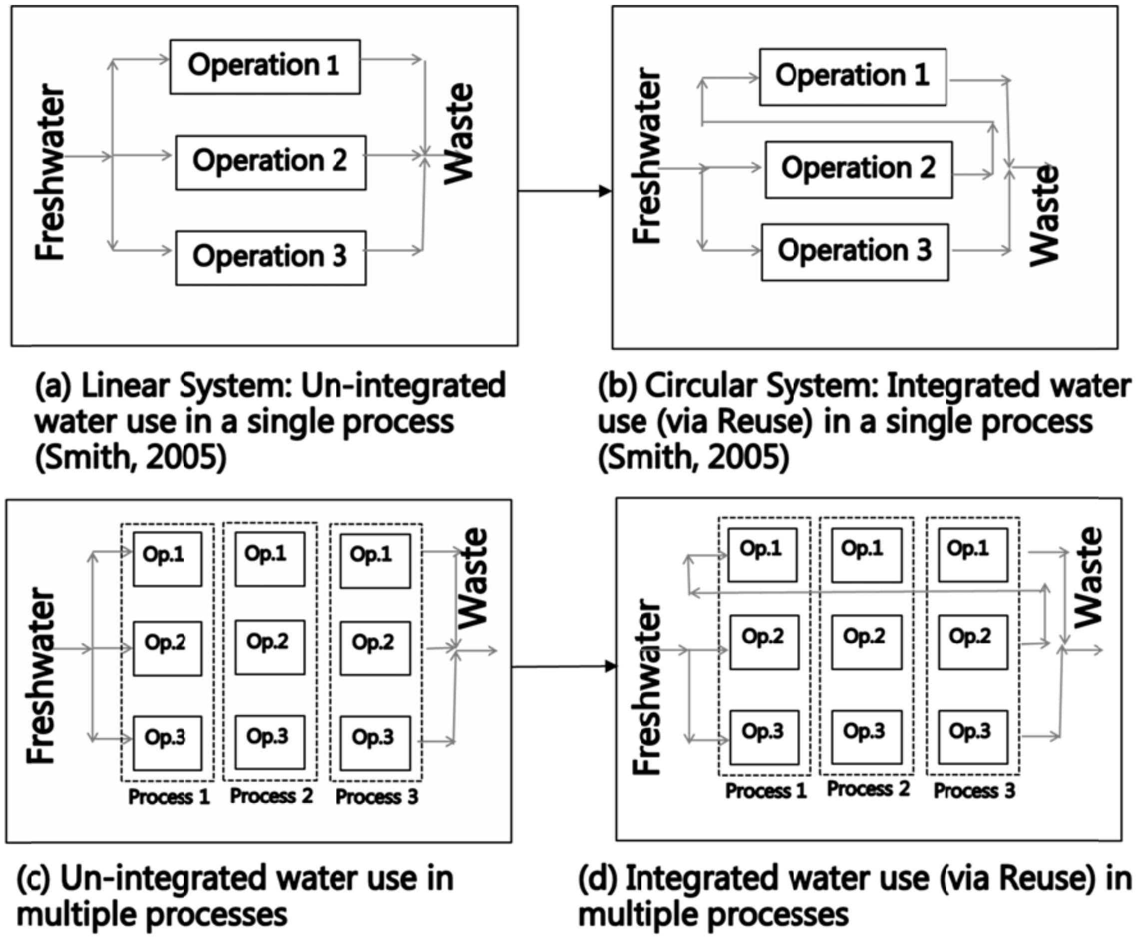


Figure 1. Water re-use concept on a local vs. global level

II.4. Research Problem Dimensions

The development of a strategic macroscopic optimization framework for water networks through direct recycling within an industrial city was carried out whilst taking into consideration the following dimensions, as illustrated in Figure 2.

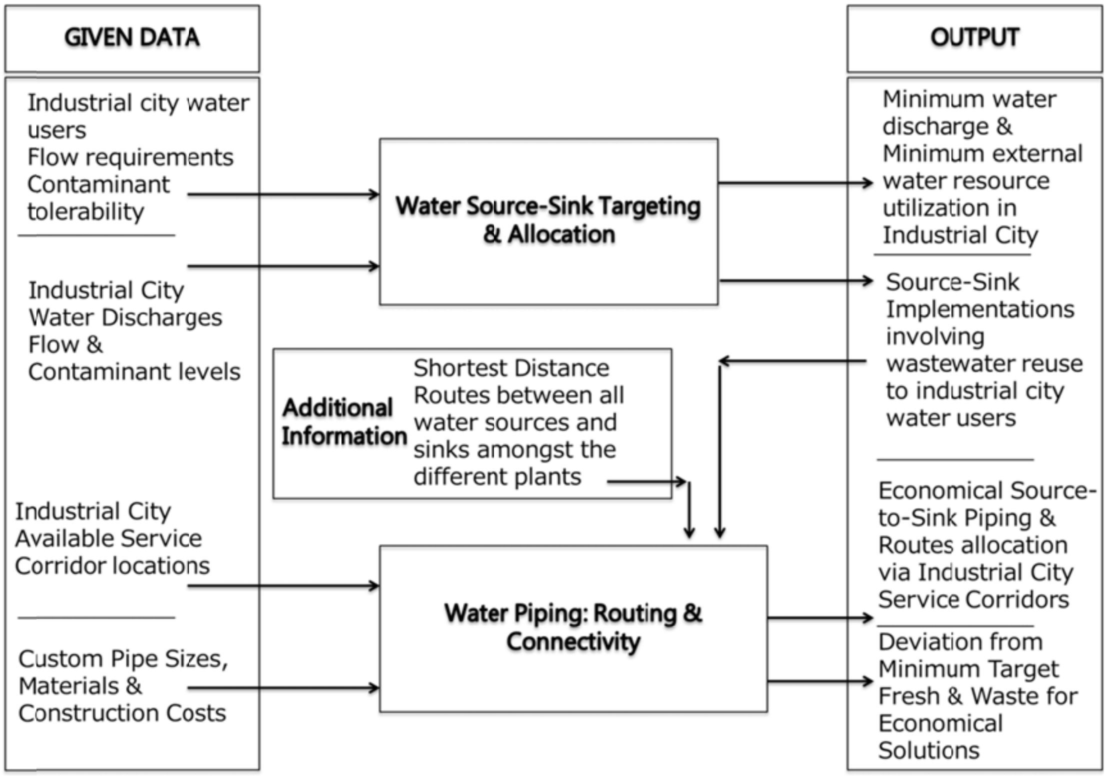


Figure 2. Required input, stipulated output and research problem dimensions

II.4.1 Water Source-Sink Targeting and Allocation

This stage necessitates the utilization of water integration direct recycle techniques, as it has been pointed out in the section discussed previously, so as to identify plausible water allocation strategies within a defined Industrial city/zone. The various water users (Sinks) and water discharges (Sources) within the different plants operating on-site need to be specified, in addition to water input data in the form of flow and contaminant concentrations. Water users need to be associated with maximum specifications for acceptable contaminant levels in order to ensure that tolerable contaminant quantities are not exceeded. Subsequently, having identified and obtained all required data, a source-sink allocation problem can be established to deliver plausible options for the assignment of certain water discharge streams to supply certain water users amongst all industrial city processing facilities that are involved. In addition to the identification of feasible source-sink allocation strategies, target limits for the minimum use of freshwater across all plants, as well as the minimum water discharge, will also be obtained.

II.4.2 Water Piping: Routing and Connectivity

This stage will focus on the formulation of a water transportation problem. This involves developing a planning model that is capable of minimizing the required total piping costs and construction expenses, for achieving desirable water integration schemes. It is important to obtain information on water source & sink locations within individual processing facilities, for which routing to and from can be provided. Moreover, proper identification of common service corridor availability, as well as access points for water sources and sinks within individual plants are essential for a convenient water transportation strategy amongst the different plants, and were considered and manifested in the solutions obtained. On another note, this work only considers the option of constructing a separate pipe associated with each source-sink allocation identified for water re-use. Information for pipe materials, as well as standard pipe diameter availability was utilized to help reflect a practical scenario. Moreover, the number of pipe bends and elbows based on the routing between corridor spaces were all obtained, so as to provide estimations for the pressure drops associated with water transportation.

II.5. Industrial City Representation

II.5.1 Layout description

A simple representation that can be used to specify any industrial city layout was defined, from which source/sink locations, corridor availability, and barriers that need to be considered whilst routing the water transportation could all be extracted. An equally spaced grid was employed to define the industrial city terrain that can be of any size. Depending on the grid spacing used, manifold uniformly-sized regions of equal area are obtained, which are then used to assemble the overall layout. Each of the regions encompassed in the industrial city zone can be assumed to be one of the following: (1) individual processing plants, (2) water sources and sinks, (3) service corridors available, (4) access ports within each plant that connect sources/sinks to available corridors, and (5) obstructions or barriers within the layout for which no infrastructure is assumed to be provided. A single plant area can involve either water sources, sinks, or a combination of both, depending on what the facility is defined to produce or consume. Each source/sink contained within a plant is accompanied with a certain location defined within the plant boundaries. The presence of corridors and access ports in the layout were considered essential in order to facilitate the water transportation, since all routes would depend on their respective locations as explained in the two sub-sections below:

II.5.1.1 Service Corridors

In order to follow industrial zone spatial plans, clearly defined corridor boundaries need to be followed for pipeline construction that in turn would facilitate the flow of water from a certain water source to a desired water sink. Service corridor arrangements will significantly impact water transportation routes between the various sources and sinks involved in different plants. Several types of service corridors can exist; therefore, the same industrial city layout can be described independently for each corridor type involved in the problem, in which each can clearly state the specifications of the types of materials carried within. For instance, examples of service corridors that could potentially involve water transport scenarios within an industrial city can include: (1) product pipes that carry aqueous liquid product streams, (2) high-pressure gas corridors are provided for pipelines that can contain water vapor, gaseous and mixed phase feed streams and products, (3) wet utility corridors that provide space for utilities such as desalinated water, cooling and potable water, (4) seawater corridors that provide space for seawater pipelines directed to industrial plants, as well as return water pipelines from industrial plants to outfall channels.

II.5.1.2 Access Ports

Since sources and sinks within a plant can lie at various different locations, depending on how the plant is operating, it could happen that some water sources and sinks are not present next to a corridor facility, but instead would need to be transported from within the plant in order to access available corridors. In such cases, it is imperative to define information regarding source and sink on-site access ports that reach common service corridor facilities. Such information will be utilized as start & end route options when considering water transportation possibilities.

When defining the industrial city layout onto the grid, each region type was associated with a different annotation in order to be able to distinguish the presence of the various entities involved. Figure 3 illustrates a small-scale example involving 2 plants, each containing a water source and a water sink.

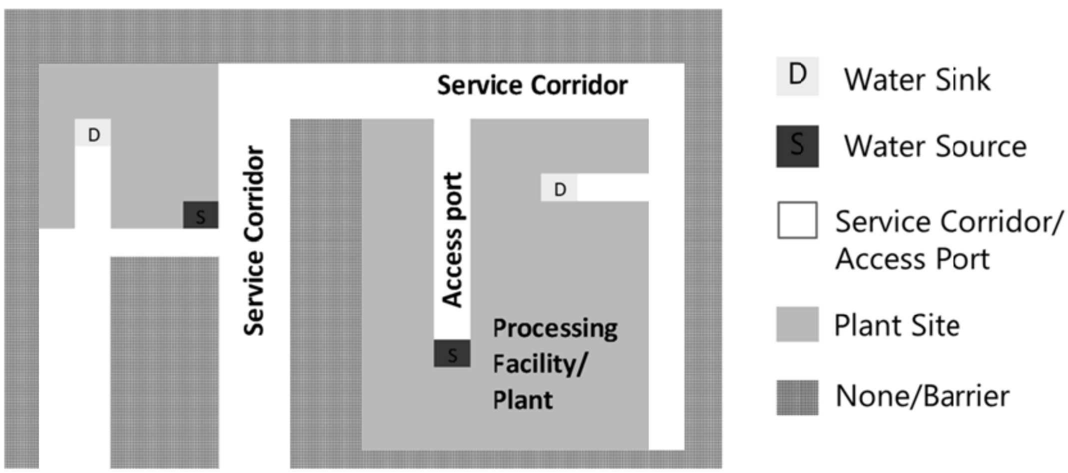


Figure 3. Required input, stipulated output and research problem dimensions

II.5.2 Routing and Piping Connectivity Options

Having defined an industrial city layout, it is then imperative to investigate piping options for water transport. Hence, based on the layout established, all the annotated uniformly-sized regions can be classified as active and inactive areas on the grid, according to the region/area type. All available areas (active regions) constitute passageways for water piping and transport. Barriers and plant infrastructure settings were excluded from the active water transportation regions. Moreover, water transport areas or active regions (i.e. sources, sinks, corridors and access ports) were associated with a central node, as well as connectivity options branching out.

Depending on the directions enabled, two different connectivity types were established. Type 1 connectivity involves only right angled directions, and thus a maximum of 4 directions to branch out to. Type 2 on the other hand, allows both right angled as well as diagonal connectivity, and thus a maximum of eight directions from a single node.

Figure 4 illustrates the pipe connectivity branching scenarios that were involved. It is very possible in certain layout arrangements that some directions need to be automatically eliminated depending on the connectivity type involved, since branching out from one node to the other to establish a connection would certainly depend on the location of consecutive nodes.

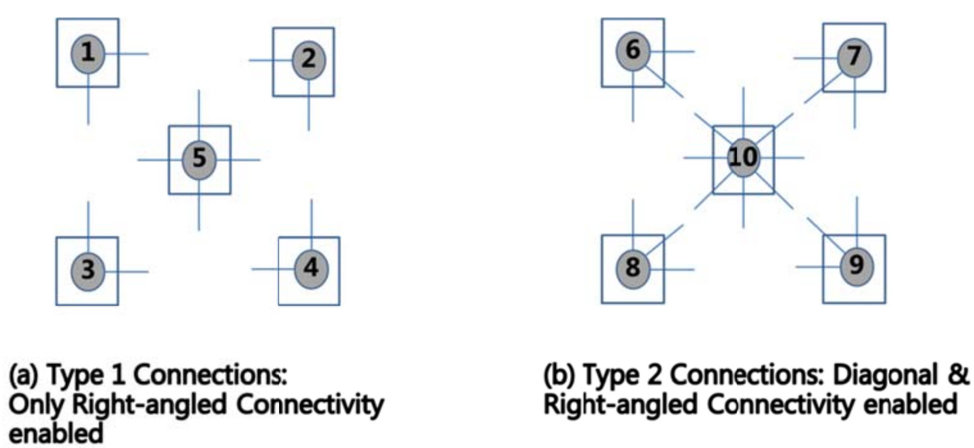


Figure 4. Piping Connectivity Options

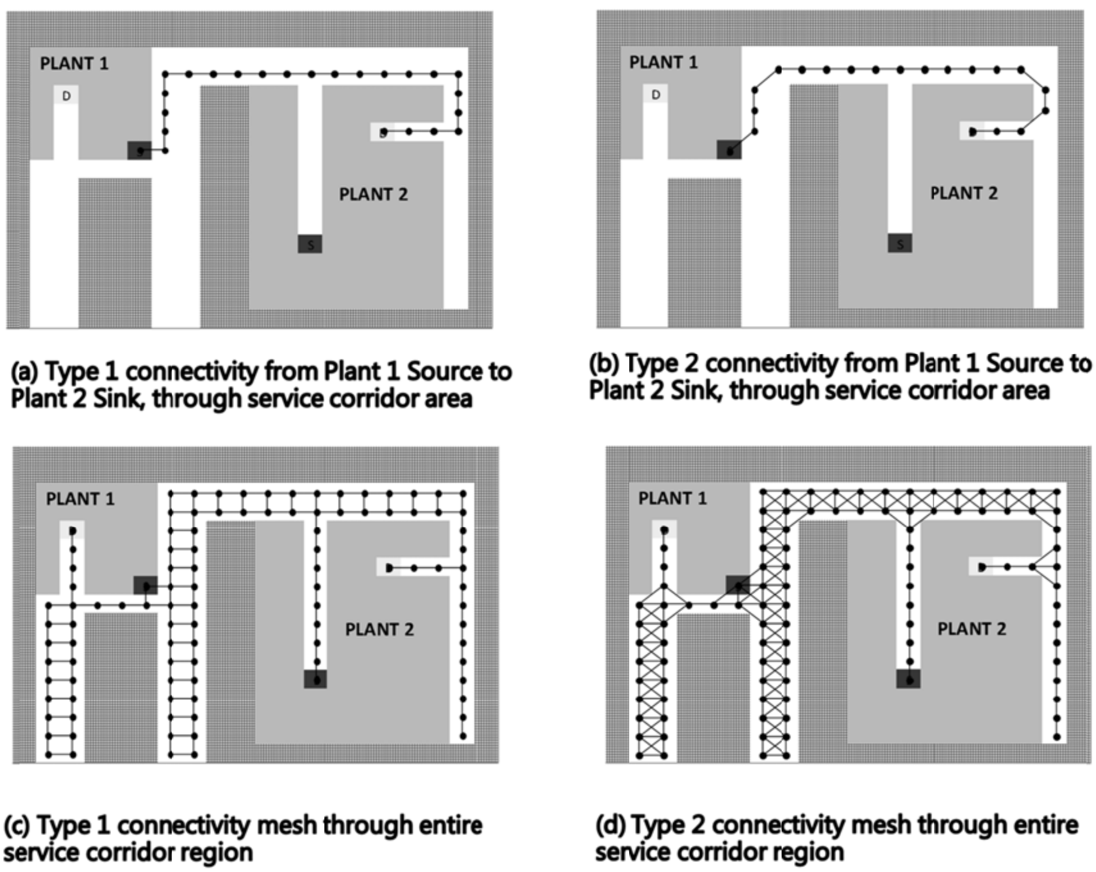
Moreover, active regions could sometimes happen to be cornered, or even involve some inactive regions in between. Such scenarios would definitely require the elimination of connectivity directions that branch out to inactive regions or infeasible corners. Therefore, when defining the existence of an edge (or connection) between two nodes, Table 1 summarizes the theory that was utilized assuming all nodes that associated with active regions constitute a finite set Z. Defining a node p as p=(x,y) with coordinates x=x(p) and y=y(p), and a node q as q=(x,y) with coordinates x=x(q) and y=y(q), the logic behind the presence of a connection between any two nodes p and q is provided in Table 1 below.

Type 1 connectivity mesh A(Z,T) thus consists of a set of nodes Z, and set of edges T. Moreover, a single path G in A is a sequence of nodes (p_1, .., p_n) such that (p_i, p_{i+1}) $\in$T for all $1 \leq i \leq n$ and p $\in$ Z. Similarly, Type 2 connectivity mesh B(Z,V) consists of the same set of nodes Z, and set of edges V, and a single path G in B is a sequence of nodes (p_1, .., p_n) such that (p_i, p_{i+1}) $\in$V for all $1 \leq i \leq n$ and p $\in$ Z.

Table 1. Connectivity Existence based on node coordinates

Connectivity Types	Logic for connectivity (edge) existence
Type 1:	$\forall\, p \in Z \;\; if\; \exists\; x(q) = x(p) + 1\; \&\; y(q) = y(p) :\; q(x, y) \in Z$ $then\; [p, q] = \{s \in T : s = \alpha p + (1 - \alpha) q, 0 \le \alpha \le 1\}\; else\; \nexists s$
Defined as a set of edges ***T***	$\forall\, p \in Z \;\; if\; \exists\; x(q) = x(p) - 1\; \&\; y(q) = y(p) :\; q(x, y) \in Z$ $then\; [p, q] = \{s \in T : s = \alpha p + (1 - \alpha) q, 0 \le \alpha \le 1\}\; else\; \nexists s$
	$\forall\, p \in Z \;\; if\; \exists\; x(q) = x(p)\; \&\; y(q) = y(p) + 1 :\; q(x, y) \in Z$ $then\; [p, q] = \{s \in T : s = \alpha p + (1 - \alpha) q, 0 \le \alpha \le 1\}\; else\; \nexists s$
	$\forall\, p \in Z \;\; if\; \exists\; x(q) = x(p)\; \&\; y(q) = y(p) - 1 :\; q(x, y) \in Z$ $then\; [p, q] = \{s \in T : s = \alpha p + (1 - \alpha) q, 0 \le \alpha \le 1\}\; else\; \nexists s$
Type 2:	$\forall\, p \in Z \;\; if\; \exists\; x(q) = x(p) + 1\; \&\; y(q) = y(p) :\; q(x, y) \in Z$ $then\; [p, q] = \{s \in V : s = \alpha p + (1 - \alpha) q, 0 \le \alpha \le 1\}\; else\; \nexists s$
Defined as a set of edges ***V***	$\forall\, p \in Z \;\; if\; \exists\; x(q) = x(p) + 1\; \&\; y(q) = y(p) + 1 :\; q(x, y) \in Z$ $then\; [p, q] = \{s \in V : s = \alpha p + (1 - \alpha) q, 0 \le \alpha \le 1\}\; else\; \nexists s$
	$\forall\, p \in Z \;\; f\; \exists\; x(q) = x(p) - 1\; \&\; y(q) = y(p) :\; q(x, y) \in Z$ $then\; [p, q] = \{s \in V : s = \alpha p + (1 - \alpha) q, 0 \le \alpha \le 1\}\; else\; \nexists s$
	$\forall\, p \in Z \;\; if\; \exists\; x(q) = x(p) - 1\; \&\; y(q) = y(p) - 1 :\; q(x, y) \in Z$ $then\; [p, q] = \{s \in V : s = \alpha p + (1 - \alpha) q, 0 \le \alpha \le 1\}\; else\; \nexists s$
	$\forall\, p \in Z \;\; if\; \exists\; x(q) = x(p)\; \&\; y(q) = y(p) + 1 :\; q(x, y) \in Z$ $then\; [p, q] = \{s \in V : s = \alpha p + (1 - \alpha) q, 0 \le \alpha \le 1\}\; else\; \nexists s$
	$\forall\, p \in Z \;\; if\; \exists\; x(q) = x(p) - 1\; \&\; y(q) = y(p) + 1 :\; q(x, y) \in Z$ $then\; [p, q] = \{s \in V : s = \alpha p + (1 - \alpha) q, 0 \le \alpha \le 1\}\; else\; \nexists s$
	$\forall\, p \in Z \;\; if\; \exists\; x(q) = x(p)\; \&\; y(q) = y(p) - 1 :\; q(x, y) \in Z$ $then\; [p, q] = \{s \in V : s = \alpha p + (1 - \alpha) q, 0 \le \alpha \le 1\}\; else\; \nexists s$
	$\forall\, p \in Z \;\; if\; \exists\; x(q) = x(p) + 1\; \&\; y(q) = y(p) - 1 :\; q(x, y) \in Z$ $then\; [p, q] = \{s \in V : s = \alpha p + (1 - \alpha) q, 0 \le \alpha \le 1\}\; else\; \nexists s$

Based on the logic provided in Table 1, and as an illustration of the theory utilized, Figure 5 shows a comparison between the connectivity scenarios that can be developed. An assembly of edges that represent a connection from Plant 1’s water source to Plant 2’s water sink is provided in Figure 5 (a) and (b). Slight differences as to how the branching is made between consecutive nodes can be noted. The complete meshes of connectivity options according to all corridor and access port spaces defined are shown in Figure 5 (c) and (d). It is evident that Type 2 has more branching options than Type 1.



(a) Type 1 connectivity from Plant 1 Source to Plant 2 Sink, through service corridor area

(b) Type 2 connectivity from Plant 1 Source to Plant 2 Sink, through service corridor area

(c) Type 1 connectivity mesh through entire service corridor region

(d) Type 2 connectivity mesh through entire service corridor region

Figure 5. Piping Connectivity illustrated for Figure 3’s Small-Scale Illustration

II.6. Shortest Paths Between Water Sources and Sinks

In order to find the shortest distance between two points given multiple routes and obstructed areas, a separate algorithm was utilized to extract all required distance information. An optimization problem that could determine water integration options, utilizing all the shortest path information between water sources and sinks within a given industrial city plot would then be carried out. There are several algorithms mentioned in literature (Levitin 2007; Cormen, Leiserson et al. 2009), and the selection included the following algorithms: Breadth-first search, Dijkstra's algorithm, A* search algorithm, Bellman-Ford algorithm, Floyd-Warshall algorithm and Johnson's algorithm. The Breadth-first search is a graph search algorithm that explores all neighboring nodes for a root node, followed by unexplored neighbor nodes associated with each of the nearest nodes to the root node till destination is reached (Damak 2010). All edges are treated equally since the weights are uniform. The weight of a path is defined to be the sum of the weights of all its edges(Zhan 2010).

Dijkstra's algorithm was introduced in 1950's (Dijkstra 1959). The algorithm solves a shortest path problem for a graph from a given source to a destination point with no negative edge path costs, producing a shortest path tree. The A* search algorithm attains single pair shortest path problems using heuristics, and is an extension of Dijkstra's algorithm (Damak 2010). Bellman–Ford's algorithm, named after its developers, Richard Bellman and Lester Ford, is a graph search algorithm that considers negative edge weights (Damak 2010). The algorithm assigns the distance to the source vertex an initial value of zero, and the distance to all other vertices an infinite value, then explores all edges whilst relaxing, or updating the distance to the destination. A final check for each edge is performed to detect negative weight cycles. Floyd-Warshall is an algorithm that uses a weighted, directed graph by multiplying an adjacency-matrix representation of the graph several times in order to solve for all pairs of shortest paths (Cormen, Leiserson et al. 2009). Floyd-Warshall requires dynamic programming since independent sub-problems are solved stored. Edges are allowed to have negative weights, but no negative weight cycles. Johnson's algorithm solves for all pairs of shortest paths in a sparse weighted, directed graph (Damak 2010). The algorithm inserts a new node with zero weighted edges to all other nodes, and runs the Bellman-Ford algorithm to check for negative weight cycles, then finds the least weight of a path from the new node to an existing node (Damak 2010). All new edges are reweighted, and for each node, Dijkstra's algorithm is used to find the least weight to other nodes.

In this work, finding the shortest distance between two points (a water source and a water sink), given multiple routes, was one of the focal aspects that needed to be effectively addressed. For this purpose, Dijkstra's shortest path algorithm was utilized. The reason it was selected over the rest was because it balances the time needed to find pathways within a plot, along with the amount of iterations required to reach the best solution heuristically. While other algorithms may accomplish the same task, Dijkstra's algorithm was highly compatible with the PHP environment used in the execution phase, and was found to be reliable in solving multiple problems, given a set of predefined sources and sinks.

II.6.1 Dijkstra's Algorithm Execution

The principle behind Dijkstra's algorithm is the comparison between all connectivity options from a source to a sink location within a plot. Following the initiation of the program, the algorithm would iterate for each defined set of nodes and their corresponding neighbors until all the shortest paths to all defined nodes have been identified. The iteration starts with a single source node and visits all neighboring nodes. It then compares the distances to these neighbors and selects the nearest unvisited neighbor. Then for each of those selected neighboring nodes, the algorithm explores their unexplored neighbor nodes, and so on, until it the target node is reached. The search is performed in a systematic manner, and avoids duplication of checks. Even after the target node is reached, the iteration will continue until everything has been visited so that it ensures no shorter path exists. Keeping in mind, all nodes included in the search are not within any obstructed region, due to the imposed active and inactive region classification. Therefore, any barrier region is automatically removed by the program and will not participate in the iterative search, since the nodes are only associated with active regions. Following the completion of the iteration the program proceeds to reverse iterate from the chosen target until it reaches the source in order to correctly display the complete sequence of nodes that constitute the final pathway for a single source/sinks mapping alternative. This allows for the extraction of all shortest pathways from a given starting set sources to a set of destinations.

The implementation for carrying out Dijkstra's algorithm was adapted from a previously developed work. A separate code was developed so that the PHP program can easily automate the input imported from MS Excel spreadsheet which consists of the defined layout of the plot and its barriers, corridors, plants, sources and sink locations as well as associated access regions. Two functions were defined in the PHP code, which act to convert a 2 dimensional table storage type into a 1 dimensional sequential storage array and vice-versa. These functions were greatly needed as the input from MS Excel was given in the form of a table, which was not compatible with conventional storage in PHP. Note that, the table may have been used if the program utilized the services of a MYSQL database which would enable a much more diverse type of storage, but it was not used in order to save coding and processing time. The MS Excel table was exported into a csv file (comma delimited table). This simplified the input and allowed it to be directly used as an array in the PHP program. Two additional arrays were implemented in order to specify all the nodes associated with sources/sinks locations. Inherently, this would also inform the program of the number of reverse iterations needed to run in total. Following the completion of array input, the program walks through each node from the csv input and defines vertices in a graph such that each vertex connects to either 4 or 8 neighbors. If an edge or a barrier is encountered the program will create from 0 to 3 neighbors based on multiple variables. The use of 4 or 8 depends on whether or not diagonal connections are allowed, as explained in Section 4.2. Diagonal edges (connections) were assigned a higher weight than the rest. The generated plot is then sent to the Dijkstra function, which produces a raw array consisting of the every node in the pathway from the source to the target.

The raw array output is then taken and used to create a table similar to the one imported from MS Excel where only the shortest path is shown. This table can be used for visualization and as an input back into MS Excel. Since the weight of a path is the sum of the weights of all its edges, the path distance was also calculated based on weight inputs of vertex-to-vertex connections based on their corresponding classifications (i.e, Type 1 or Type 2). Finally the angles along the shortest path are calculated in order to easily determine the number of elbows within the path, in order to be used for pressure drop calculations.

II.7. Water Integration Problem Statement and Mathematical Formulation

The problem statement can be summarized as follows: Given an industrial city scheme encompassing multiple plants P, each containing a set of water sources SU_p and a set of water sinks SN_p, it is required to develop a strategy for optimal water reuse and recycle across individual processes, in the form of a water network design that would in turn allow for effective and economical global water resource conservation across the industrial city. The solutions need to offer attractive economic operations and environmental benefits (in the form of reduced wastewater disposal) when compared to the scenario involving all plants as stand-alone processing facilities operating separately.

The standard Non-Linear Problem (NLP) mathematical objective of fresh (and waste) targeting that was used is as follows.

$$Minimize\ \sum\sum_{p \in P\ j \in SN_p} F_{jp} \tag{1}$$

It should be pointed out that the targeting stage is independent of the of network structure, and is carried out based on conventional water pinch theories. Additionally, single contaminant material recycle pinch diagrams can offer insight in terms of the targets that can be achieved.

The Non-Linear Problem (NLP) mathematical formulation with minimum piping cost embedded into the objective function was defined as follows:

$$Minimize.\ \ \gamma\left[\sum\sum\sum_{p\in P\ i\in SU_p\, j\in SN_p} a\left(DI_{ip,jp'}^{c}\right)^{b} L_{ip,jp'} + \sum\sum_{p\in P\ j\in SN_p} a\left(DI_{jp}^{c}\right)^{b} L_{jp} + \sum\sum_{p\in P\ i\in SU_p} a\left(DI_{ip}^{c}\right)^{b} L_{ip}\right] + H_y C^{FRESH} \sum\sum_{p\in P\ j\in SN_p} F_{jp} \quad (2)$$

Equations (3)-(5) describe the mass balances around water sources, water sinks, and the component balance around water sinks respectively. The summations of all terms must equal the values provided for available water source flowrates W_{ip}, and the specified sink flow required G_{jp}. Equation (6) describes the allowable sink contaminant range, according to the maximum and minimum tolerable pollutant information that is associated with each sink. Equations (7)-(9) were used to specify non-negativity conditions for flowrates.

$$\sum\sum_{p\in P\ j\in SN_p} M_{ip,jp'} + D_{ip} = W_{ip} \quad \forall p,p' \in P \quad \forall i \in SU_p \quad (3)$$

$$\sum\sum_{p\in P\ i\in SU_p} M_{ip,jp'} + F_{jp} = G_{jp} \quad \forall p,p' \in P \quad \forall j \in SN_p \quad (4)$$

$$\sum\sum_{p\in P\ i\in SU_p} M_{ip,jp'}\, x_{c,ip}^{Source} + F_{jp} x_c{}^{FRESH} = G_{jp} z_{c,jp}^{in}$$

$$\forall p,p' \in P;\ \ \forall j \in SN_p\ ;\ \forall c \in C \quad (5)$$

$$z_{c,jp}^{min} \le z_{c,jp}^{in} \le z_{c,jp}^{max} \quad (6)$$

$$M_{ip,jp'} \ge 0 \qquad \forall p,p' \in P\ ;\ \forall j \in SN_p\ ;\forall i \in SU_p \quad (7)$$

$$D_{ip} \geq 0 \qquad \forall p \in P;\ \forall i \in SU_p \tag{8}$$

$$F_{jp} \geq 0 \qquad \forall p \in P\ ;\ \forall j \in SN_p \tag{9}$$

As described above, two objective functions are utilized in this work. The first objective (Equation (1)) was used for targeting freshwater consumption and wastewater discharge, based on provided water source and sink data in terms of flow rates and contaminant information. The second objective (Equation (2)) minimizes piping and freshwater costs of the interplant water network design. Hence, the solutions are developed based on a water reuse strategy that achieves a minimized cost. The constraints given by Equations (3)-(9) were applied in both optimization problems.

The optimum pipe diameters were found according to recommended velocity ranges (Peters, Timmerhaus et al. 2003) and are described by equations (10)-(12).

$$DI_{ip,jp'} = 0.363\left(\left(\frac{M_{ipjp'}}{\rho}\right)^{0.45} \rho^{0.13}\right) \quad \forall p,p' \in P\ ;\ \forall j \in SN_p\ ;\forall i \in SU_p \tag{10}$$

$$DI_{ip} \quad = 0.363\left(\left(\frac{D_{ip}}{\rho}\right)^{0.45} \rho^{0.13}\right) \qquad \forall p \in P;\ \forall i \in SU_p \tag{11}$$

$$DI_{jp} \quad = 0.363\left(\left(\frac{F_{jp}}{\rho}\right)^{0.45} \rho^{0.13}\right) \qquad \forall p \in P\ ;\ \forall j \in SN_p \tag{12}$$

Since pipe diameters are often available in standard sizes, all piping diameters were then obtained by rounding up calculated diameter values to an appropriate value that would reflect a standard size, according to Equations (13)-(15) .

$$DI^c_{ip,jp'} \ = Roundup\left(DI_{ip,jp'}\right) \qquad \forall p,p' \in P,\ \forall j \in SN_p\ ;\ \forall i \in SU_p \tag{13}$$

$$DI^c_{ip} \quad = Roundup\left(DI_{ip}\right) \qquad \forall p \in P\ ,\forall i \in SU_p \tag{14}$$

$$DI^c_{jp} \quad = Roundup(DI_{jp}) \qquad \forall p \in P\ ,\forall j \in SN_p \tag{15}$$

Moreover, since water transport would be associated with some pressure drops being carried in a pipeline, the Equations (16)-(36) were used for determining pressure drop levels (Geankoplis 2008). Equations (16)-(18) were used to compute the velocities.

$$v_{ip,jp'} = \frac{4M_{ipjp'}}{\pi\left(DI^{C}_{ipjp'}\right)^{2}\rho} \qquad \forall p,p' \in P;\ \forall j \in SN_p\ ; \forall i \in SU_p \tag{16}$$

$$v_{ip} = \frac{4D_{ip}}{\pi\left(DI^{C}_{ip}\right)^{2}\rho} \qquad \forall p \in P;\ \forall i \in SU_p \tag{17}$$

$$v_{jp} = \frac{4F_{jp}}{\pi\left(DI^{C}_{jp}\right)^{2}\rho} \qquad \forall p \in P;\ \forall j \in SN_p \tag{18}$$

All Reynolds number calculations were obtained according to Equations (20)-(22):

$$N_{Re_{ip,jp'}} = \frac{DI^{C}_{ip,jp'} v_{ipjp'}\rho}{\mu} \qquad \forall p,p' \in P, \forall j \in SN_p, \forall i \in SU_p \tag{19}$$

$$N_{Re_{ip}} = \frac{DI^{C}_{ip} v_{ip}\rho}{\mu} \qquad \forall p \in P, \forall i \in SU_p \tag{20}$$

$$N_{Re_{jp}} = \frac{DI^{C}_{jp} v_{jp}\rho}{\mu} \qquad \forall p \in P\ , \forall j \in SN_p \tag{21}$$

Subsequently, fanning friction factors were calculated for based on Churchill's equations (Geankoplis 2008), according to Equations (23)-(25):

$$f_{ip,jp'} = 8\left[\left(\frac{8}{N_{Re_{ip,jp'}}}\right)^{12} + \left(\frac{1}{A_{ipjp'} + \left(\frac{37530}{N_{Re_{ip,jp'}}}\right)^{16}}\right)^{1.5}\right]^{\frac{1}{12}}$$

$$\forall p,p' \in P; \forall j \in SN_p\ ; \forall i \in SU_p \tag{22}$$

$$f_{ip} = 8\left[\left(\frac{8}{N_{Re_{ip}}}\right)^{12} + \left(\frac{1}{A_{ip} + \left(\frac{37530}{N_{Re_{ip}}}\right)^{16}}\right)^{1.5}\right]^{\frac{1}{12}}$$

$\forall p \in P; \forall i \in SU_p$ (23)

$$f_{jp} = 8\left[\left(\frac{8}{N_{Re_{jp}}}\right)^{12} + \left(\frac{1}{A_{jp}+\left(\frac{37530}{N_{Re_{jp}}}\right)^{16}}\right)^{1.5}\right]^{\frac{1}{12}}$$

$\forall p \in P;\ \forall j \in SN_p$ (24)

Churchill parameters were found according to Equations (25)-(27) (Geankoplis 2008):

$$A_{ip,jp'} = \left[-2.457\ln\left(\left(\frac{7}{N_{Re_{ipjp'}}}\right)^{0.9} + 0.27\frac{\varepsilon}{DI^{c}_{ipjp'}}\right)\right]^{16}$$

$\forall p, p' \in P, \forall j \in SN_p\ ; \forall i \in SU_p$ (25)

$$A_{ip} = \left[-2.457\ln\left(\left(\frac{7}{N_{Re_{ip}}}\right)^{0.9} + 0.27\frac{\varepsilon}{DI^{c}_{ip}}\right)\right]^{16}$$

$\forall p \in P;\ \forall i \in SU_p$ (26)

$$A_{jp} = \left[-2.457\ln\left(\left(\frac{7}{N_{Re_{jp}}}\right)^{0.9} + 0.27\frac{\varepsilon}{DI^{c}_{jp}}\right)\right]^{16}$$

$\forall p \in P;\ \forall j \in SN_p$ (27)

All friction losses were computed according to Equations (28)-(30) (Geankoplis 2008):

$$\Delta F^{f}_{ipjp'} = \frac{\left(\frac{4f_{ipjp'}L_{ip,jp'}}{DI^{C}_{ip,jp'}}+K_{ex}+K_c+K_bN^{E}_{ipjp'}\right)v_{ipjp'}{}^{2}}{2}$$

$\forall p, p' \in P\ ;\ \forall j \in SN_p;\ \forall i \in SU_p$ (28)

$$\Delta F_{ip}^{f} = \frac{\left(\frac{4f_{ip}L_{ip}}{DI_{ip}^{C}} + K_{ex} + K_c + K_b N_{ip}^{E}\right) v_{ip}{}^{2}}{2}$$

$$\forall p \in P;\ \forall i \in SU_p \tag{29}$$

$$\Delta F_{jp}^{f} = \frac{\left(\frac{4f_{jp}L_{jp}}{DI_{jp}^{C}} + K_{ex} + K_c + K_b N_{jp}^{E}\right) v_{jp}{}^{2}}{2}$$

$$\forall p \in P;\ \forall j \in SN_p \tag{30}$$

Finally, pressure drops were computed from friction losses, and power requirements that are needed to overcome calculated pressure drops were then obtained by using Equations (31)-(33), and (34)-(36) respectively:

$$\Delta P_{ip,jp'}^{Drop} = \rho_{ipjp'} \Delta F_{ipjp'}^{f} \qquad \forall p, p' \in P, \forall j \in SN_p, \forall i \in SU_p \tag{31}$$

$$\Delta P_{ip}^{Drop} = \rho_{ipjp'} \Delta F_{ip}^{f} \qquad \forall p \in P \forall i \in SU_p \tag{32}$$

$$\Delta P_{jp}^{Drop} = \rho_{jp} \Delta F_{jp}^{f} \qquad \forall p \in P, \forall j \in SN_p \tag{33}$$

$$P_{ip,jp'}^{W} = \frac{g(M_{ip,jp'})(0.0001 P_{ip,jp'}^{Drop})}{3.6\times 10^{6}\ \eta} \qquad \forall p, p' \in P; \forall j \in SN_p; \forall i \in SU_p \tag{34}$$

$$P_{ip}^{w} = \frac{g(D_{ip})(0.0001 P_{ip}^{Drop})}{3.6\times 10^{6}\ \eta} \qquad \forall p \in P;\ \forall i \in SU_p \tag{35}$$

$$P_{jp}^{w} = \frac{g(F_{jp})(0.0001 P_{jp}^{Drop})}{3.6\times 10^{6}\ \eta} \qquad \forall p \in P, \forall j \in SN_p \tag{36}$$

The optimization problem was solved using “what’sBest9.0.5.0” LINDO Global Solver for Microsoft Excel 2010 , and run on a desktop PC (Intel® Core ™ i7-2620M, 2.7 GHz, 8.00 GB RAM, 64-bit Operating System).

The approach to the problem was therefore carried out as follows: (1) defining an industrial city layout to be studied, plant arrangements, source and sink locations, available corridors and any barriers in between, using the representation that has been defined; (2) extracting optimum source-sink routing, and associated path distances, to be utilized for designing economical water network piping arrangements; (3) executing a water integration problem using the provided mathematical formulation so as to determine viable and optimum source-sink implementations that involve wastewater reuse within industrial city processing facilities.

II.8. Case Study Illustration

An artificial case study was carried out as an illustration to the aspects considered in this work. The notion of water integration through direct recycling within industrial city infrastructures has been examined for several different cases, with their respective spatial layouts considered Figure 6 shows the overall industrial city arrangement that has been considered, which consists of a total of 6 plants, a total of 6 water sources, and 6 water sinks distributed across all plants. The plot was assumed to have a total area of 64 km^2, spread over a total of 1600 equally-spaced regions, each region corresponding to 0.04 km^2 of area. Moreover, the respective arrangements of the plants, barriers, as well as service corridors available for water transport were all assumed, in addition to the locations of the various water sources and sinks, for the purpose of illustrating the methodology that has been proposed. However, it should be pointed out that the representation can easily accommodate different cases of industrial city arrangements once provided, which greatly assists in the planning for effective designs of interplant water networks, regardless of the layout dimensions or the respective arrangement of plants involved.

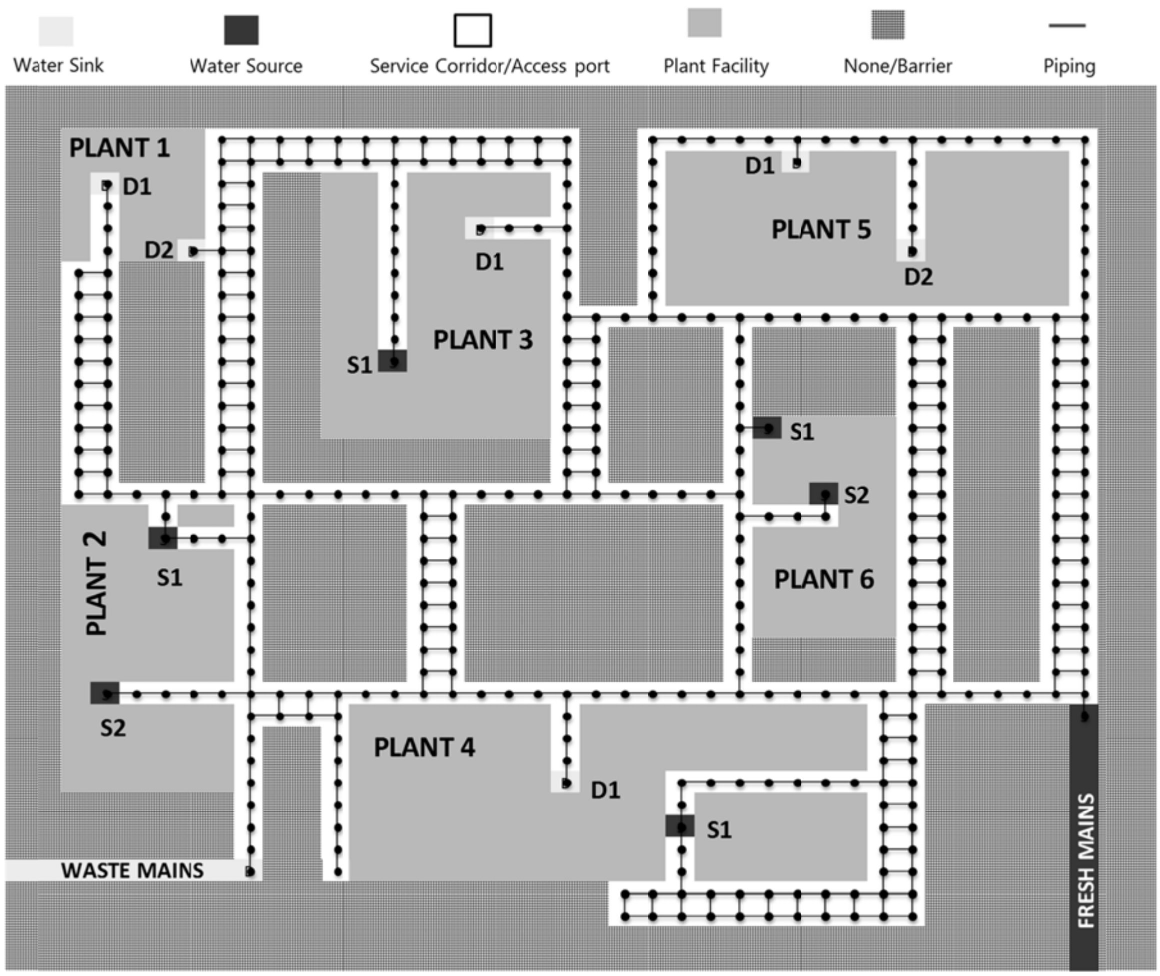


Figure 6. Industrial City Case Study Layout, with Type 1 connectivity mesh illustrated

Collective fresh and waste mains were utilized, that supply freshwater to all plants, and receive disposed wastewater from all plants respectively. Independent fresh and wastewater mains could be assumed for a single plant facility, by specifying their respective locations on the plot, as needed. Moreover, additional information would need to be provided as to which of each fresh mains can water be obtained from for a given plant, and to which waste mains could receive the plant's disposed water. In this case study, fresh and waste mains were kept shared to and from all plants involved, as demonstrated in Figure 6. Two different scenarios have been assumed for the locations of fresh and waste mains by having their respective positioning altered, in order to investigate whether the piping costs are drastically affected. Figure 6 demonstrates the first scenario, whereas Figure 7 shows the second scenario when their respective positions are switched. For each of these two cases, the two different connectivity options were implemented. Type 1 connectivity mesh is illustrated in Figure 6, and Type 2 is given in Figure 7. Thus, a total of four different settings were assumed when extracting the shortest path distances using Dijkistra's algorithm.

All active regions (i.e, water sources, sinks, corridors and access ports) were labeled, based on the industrial city layout that has been assumed in order to identify all nodes associated with active regions, and thus easily extract the shortest pathways that connect each source to all destinations involved. Distance information that has been obtained by executing Dijkistra's algorithm is provided in Tables 2-5, for all scenarios that have been considered. Moreover, information regarding how many elbows and bends are associated with the shortest paths extracted have also been obtained and provided in Tables 2-5, so as to be used in pressure drop calculations.

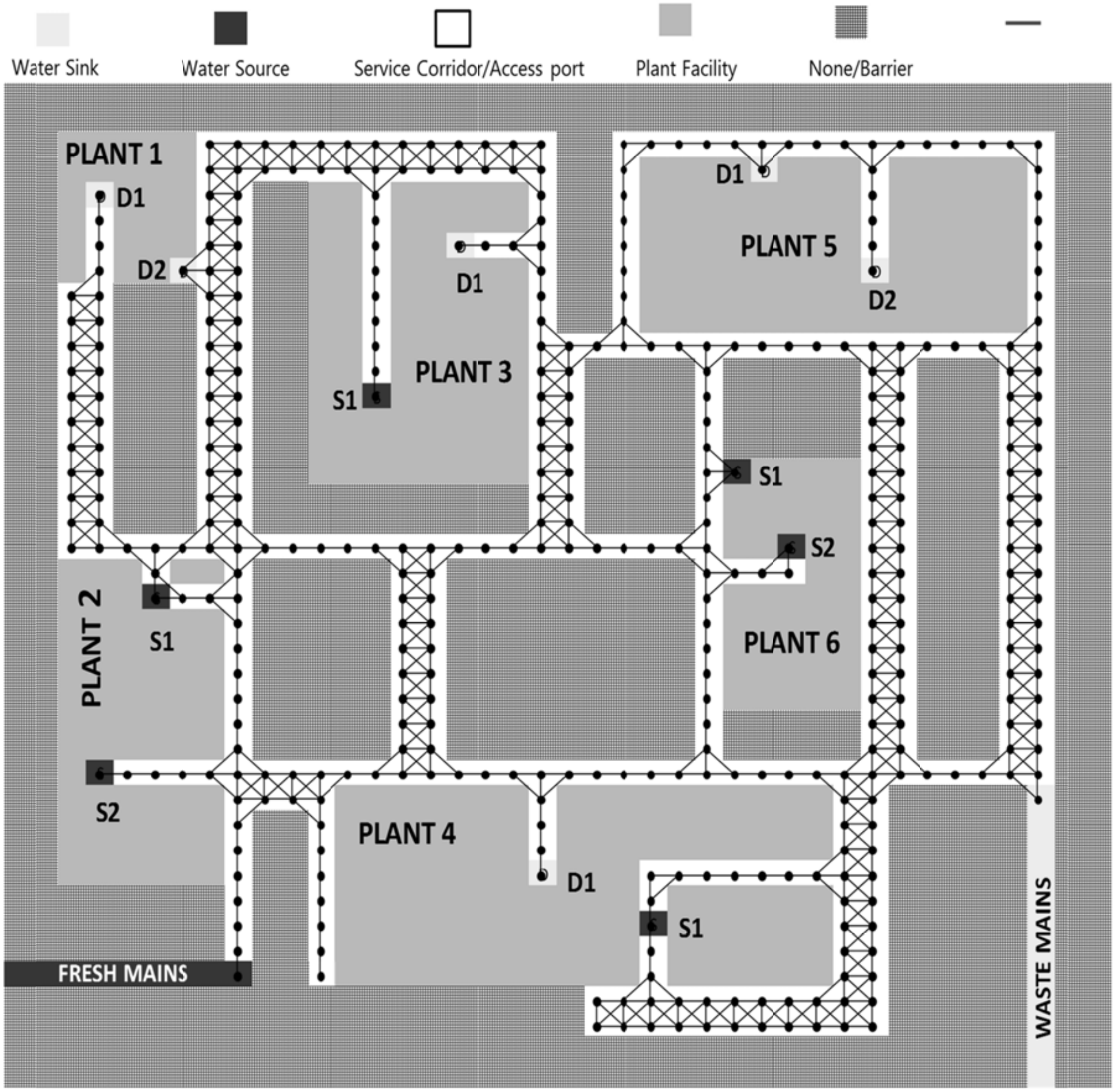


Figure 7. Industrial City Layout (Fresh and Waste mains positioning switched), with Type 2 connectivity mesh illustrated

Table 2. Case 1,5 shortest distance data extracted and total number of edges using right-angled pathways within corridors (Original Layout)

Path Distance (km)	(P1D1)	(P1D2)	(P3D1)	(P4D1)	(P5D1)	(P5D2)	(WASTE)
(P2S1)	3.6	3.2	6.2	5	8.2	9.8	3.6
90^0 Edges	2	3	4	3	7	7	1
(P2S2)	5.4	5	8	4	10	11.6	2.6
90^0 Edges	3	4	4	1	7	7	1
(P3S1)	9.6	4	4.2	10.2	7.8	9.4	9.2
90^0 Edges	4	3	3	6	6	6	2
(P4S1)	12.6	11.4	9.6	5.6	10.4	11.2	8.6
90^0 Edges	6	7	7	4	8	6	6
(P6S1)	8	6.8	3.8	4.6	4.6	6.2	7.6
90^0 Edges	3	4	4	3	5	5	5
(P6S2)	8.2	7	4.8	4.4	5.6	7.2	7.4
90^0 Edges	4	5	5	4	6	6	6
(FRESH)	11.6	10.4	8.6	4.6	7.4	7.4	7.6
90^0 Edges	4	5	5	2	2	2	4

Table 3. Case 2,6 shortest distance data extracted and total number of edges using right-angled pathways within corridors (Switching positioning of Fresh and Waste Mains)

Path Distance (km)	(P1D1)	(P1D2)	(P3D1)	(P4D1)	(P5D1)	(P5D2)	(WASTE)
(P2S1)	3.6	3.2	6.2	5	8.2	9.8	8
90^0 Edges	2	3	4	3	7	7	3
(P2S2)	5.4	5	8	4	10	11.6	7
90^0 Edges	3	4	4	1	7	7	1
(P3S1)	9.6	4	4.2	10.2	7.8	9.4	11.6
90^0 Edges	4	3	3	6	6	6	4

Table 3. Continued

Path Distance (km)	(P1D1)	(P1D2)	(P3D1)	(P4D1)	(P5D1)	(P5D2)	(WASTE)
(P4S1)	12.6	11.4	9.6	5.6	10.4	11.2	4.2
90^0 Edges	6	7	7	4	8	6	4
(P6S1)	8	6.8	3.8	4.6	4.6	6.2	5.2
90^0 Edges	3	4	4	3	5	5	3
(P6S2)	8.2	7	4.8	4.4	5.6	7.2	5
90^0 Edges	4	5	5	4	6	6	4
(FRESH)	7.2	6	8.6	4.6	10.6	12.2	7.6
90^0 Edges	4	3	7	4	10	10	4

Table 4. Case 3,7 shortest distance data extracted and total number of edges using diagonally integrated pathways within corridors (Original Layout)

Path Distance (km)	(P1D1)	(P1D2)	(P3D1)	(P4D1)	(P5D1)	(P5D2)	(WASTE)
(P2S1)	3.36	2.84	5.72	4.64	7.24	8.84	3.36
135^0 Edges	2	3	6	6	9	10	4
(P2S2)	5.04	4.52	7.28	3.88	8.8	10.4	2.48
135^0 Edges	4	5	10	2	13	14	2
(P3S1)	9	3.52	3.84	9.48	7.08	8.68	8.96
135^0 Edges	8	5	6	12	11	12	4
(P4S1)	11.64	10.32	8.64	5.12	9.44	10.24	8
135^0 Edges	12	13	16	8	15	14	8
(P6S1)	7.64	6.2	3.32	4.24	4	5.6	6.76
135^0 Edges	5	6	7	5	8	9	9
(P6S2)	7.84	6.4	4.2	3.92	4.88	6.48	6.8
135^0 Edges	5	6	10	7	11	12	7
(FRESH)	10.88	9.56	7.88	4.36	7.16	7.16	7.24
135^0 Edges	7	8	11	3	3	4	3

Table 5. Case 4,8 shortest distance data extracted and total number of edges using diagonally integrated pathways within corridors (Switching positioning of Fresh and Waste Mains)

Path Distance (km)	**(P1D1)**	**(P1D2)**	**(P3D1)**	**(P4D1)**	**(P5D1)**	**(P5D2)**	**(WASTE)**
(P2S1)	3.36	2.84	5.72	4.64	7.24	8.84	7.64
135^0 Edges	2	3	6	6	9	10	5
(P2S2)	5.04	4.52	7.28	3.88	8.8	10.4	6.88
135^0 Edges	4	5	10	2	13	14	1
(P3S1)	9	3.52	3.84	9.48	7.08	8.68	10.76
135^0 Edges	8	5	6	12	11	12	11
(P4S1)	11.64	10.32	8.64	5.12	9.44	10.24	3.6
135^0 Edges	12	13	16	8	15	14	7
(P6S1)	7.64	6.2	3.32	4.24	4	5.6	4.84
135^0 Edges	5	6	7	5	8	9	4
(P6S2)	7.84	6.4	4.2	3.92	4.88	6.48	4.52
135^0 Edges	5	6	10	7	11	12	6
(FRESH)	6.72	5.76	7.76	4.24	9.28	10.88	7.24
135^0 Edges	4	1	12	6	15	16	5

When comparing the data in Tables 2 and 3 to Tables 4 and 5, it can be noted that Type 2 connectivity provides path options with slightly shorter distances, as compared to Type 1. Moreover, when evaluating the original layout, against having the fresh and waste mains positions interchanged, the distances from the fresh mains to all water sinks is reduced, even though the number of elbows in the pipeline was found to increase in some pathways. Moreover, three out of a total of seven distances that associate the water sources to the waste mains decrease, and two out of the seven distances between the fresh mains and the water sinks decrease after implementing this interchange.

Having obtained all required data for shortest paths within corridors, two different scenarios have been considered for contaminant information: (a) single contaminant and (b) multiple contaminants. It should be pointed out that for illustration purposes, all flowrate and contaminant composition values were assumed in this case study. However, in case real data may be obtainable, similar analysis is certainly possible. For each of these two contaminant scenarios all the four settings in terms of distance information that are provided in Tables 2-5 have been assumed.

II.8.1 Single Contaminant Considered

Table 6 provides flowrate and contaminant composition data that were utilized when considering a single contaminant in the problem for water integration, via direct recycling amongst the different plants within the industrial city plot that has been assumed.

Table 6. Single Contaminant Source and Sink Data

Water Sources	Flow (ton/h)	Conc. (ppm)	Load (kg/h)	Water Sinks	Flow (ton/h)	Max. Inlet Conc. (ppm)	Load (kg/h)
P2S1	80	140	11.2	P1D2	80	50	4
P2S2	120	100	12	P1D1	120	0	0
P3S1	140	180	25.2	P3D1	80	50	4
P4S1	100	100	10	P4D1	195	240	46.8
P6S2	80	230	18.4	P5D1	140	140	19.6
P6S1	195	250	48.75	P5D2	80	170	13.6

When minimizing the global freshwater consumption as the objective, a total of 200t/h and 220 t/h of minimum fresh and waste were attained respectively. When minimizing the total freshwater expenditures plus piping costs required for achieving interplant water integration, a source-sink mapping implementation that satisfies target values for fresh and waste has been obtained for all Cases (1-4). Table 7 provides the matching flowrates that were found when minimizing the cost of the network. All cases gave the same implementation, thus indicating a single optimum source-sink mapping solution despite the minor deviations in the scenarios involved.

Table 7. Optimum Piping Cost Source-Sink mapping Implementation obtained for a single contaminant

Flow kg/h	P1D1	P1D2	P3D1	P4D1	P5D1	P5D2	Waste
P2S1	0	0	0	80,000	0	0	0
P2S2	0	0	0	60,000	60,000	0	0
P3S1	0	0	0	0	70,000	70,000	0
P4S1	0	40,000	40,000	0	10,000	10,000	0
P6S1	0	0	0	0	0	0	195,000
P6S2	0	0	0	55,000	0	0	25,000
Fresh	120,000	40,000	40,000	0	0	0	0

Table 8 provides the pressure drops obtained for all the cases, and the results show that all lie in the range of 1~25 bar, having the upper end of the pressure drop range associated with instances involving larger distances between the water sources and the respective destination, as well as increased flows in the corresponding pipelines. A 0.75 loss at pipe elbow/bend factor was utilized for the 90^0 angle bends, as recommended by Geankoplis (2008).

Table 8. Pressure drops obtained in pipes for cases assuming a single contaminant scenario

Pressure Drop (bar)	P1D1	P1D2	P3D1	P5D1	P5D2	P4D1	Waste
	Case1- Right Angled Pathways only Original Positioning of Fresh and Waste Mains						
P2S2	0	0	0	5.76	0	2.30	0
P2S1	0	0	0	0	0	4.87	0
P3S1	0	0	0	5.95	7.17	0	0
P6S2	0	0	0	0	0	2.17	25.48
P6S1	0	0	0	0	0	0	5.24
P4S1	0	3.15	2.65	6.82	7.34	0	0
Fresh	23.86	2.87	2.38	0	0	0	0
	Case 2- Right Angled Pathways only, Switched Positioning of Fresh and Waste Mains						
P2S2	0	0	0	5.76	0	2.30	0
P2S1	0	0	0	0	0	4.87	0
P3S1	0	0	0	5.95	7.17	0	0
P6S2	0	0	0	0	0	2.17	17.22
P6S1	0	0	0	0	0	0	3.59
P4S1	0	3.15	2.65	6.82	7.34	0	0
Fresh	14.82	1.66	2.38	0	0	0	0
	Case 3-Diagonally Integrated Pathways, Original Positioning of Fresh and Waste Mains						
P2S2	0	0	0	5.07	0	2.23	0
P2S1	0	0	0	0	0	4.52	0
P3S1	0	0	0	5.41	6.63	0	0
P6S2	0	0	0	0	0	1.93	23.41
P6S1	0	0	0	0	0	0	4.67
P4S1	0	2.85	2.39	6.19	6.71	0	0
Fresh	22.39	2.64	2.18	0	0	0	0
	Case 4-Diagonally Integrated Pathways, Switched Positioning of Fresh and Waste Mains						
P2S2	0	0	0	5.07	0	2.23	0
P2S1	0	0	0	0	0	4.52	0
P3S1	0	0	0	5.41	6.63	0	0
P6S2	0	0	0	0	0	1.93	15.57
P6S1	0	0	0	0	0	0	3.34
P4S1	0	2.85	2.39	6.19	6.71	0	0
Fresh	13.83	1.59	2.15	0	0	0	0

II.8.2 Multiple Contaminants Considered

Tables 9 and 10 provide flowrate and contaminant composition data for the case of multiple contaminants being considered (3 in this illustration) in the water integration problem.

Table 9. Multiple Contaminant Source Data

SOURCES	Flow ton/h	Conc. X1(ppm)	Conc. X2 (ppm)	Conc. X3 (ppm)
P2S1	80	140	100	60
P2S2	120	100	50	30
P4S1	100	100	190	210
P3S1	140	180	150	130
P6S1	195	250	190	200
P6S2	80	230	180	180

Table 10. Multiple Contaminant Sink Data

SINKS	Flow ton/h	Max. Inlet Conc. X1(ppm)	Max. Inlet Conc. X2 (ppm)	Max. Inlet Conc. X3(ppm)
P1D1	120	0	0	30
P1D2	80	50	50	80
P3D1	80	50	70	100
P4D1	195	240	130	150
P5D1	140	140	100	100
P5D2	80	170	120	130

A total of 226.8t/h and 246.8 t/h of minimum fresh and wastewater targets were found respectively, which are evidently higher than the single contaminant case, as the problem becomes more constrained. It was found that the piping costs associated with the target value of the freshwater being used in all sinks, as well as the corresponding target wastewater from all sources going to waste to also be the least expensive option. However, when minimizing the total piping and freshwater costs based on the objective function provided in Equation (2), an implementation that satisfies both the freshwater and wastewater targets of 226.8t/h and 246.8 t/h respectively was found, and is provided in Table 11.

Table 11. Optimum Piping Cost Source-Sink mapping Implementation obtained for multiple contaminants

Flow kg/h	P1D1	P1D2	P3D1	P4D1	P5D1	P5D2	Waste
P2S1	0	0	0	0	32,000	48,000	0
P2S2	0	25,714	14,286	66,263	13,737	0	0
P3S1	0	0	0	40,579	67,421	32,000	0
P4S1	0	14,286	25,714	0	0	0	60,000
P6S1	0	0	0	8,158	0	0	186,842
P6S2	0	0	0	80,000	0	0	0
Fresh	120,000	40,000	40,000	0	26,842	0	0

Moreover, similar to the single contaminant scenarios, the same implementation was obtained for all the cases (5-8) involving multiple contaminant information, with no deviations from minimum fresh and waste targets. Table 12 provides the pressure drop values obtained, and all of which were found to lie in the range of 1~34 bar. The range slightly decreases when compared to the single contaminant cases, due since a 0.5 loss at pipe elbow/bend factor was utilized for the 135^0 angle bends that are associated with the diagonal paths extracted.

Table 12. Pressure drops obtained in pipes for cases assuming a multiple contaminant scenario

Pressure Drop (bar)	P1D1	P1D2	P3D1	P5D1	P5D2	P4D1	Waste
	Case 5- Right Angled Pathways only Original Positioning of Fresh and Waste Mains						
P2S2	0	18.13	9.94	11.58	0	2.76	0
P2S1	0	0	0	1.52	3.77	0	0
P3S1	0	0	0	5.56	1.74	2.89	0
P6S2	0	0	0	0	0	4.29	0
P6S1	0	0	0	0	0	2.10	4.85
P4S1	0	14.17	34.81	0	0	0	4.95
Fresh	23.86	2.87	2.38	2.90	0	0	0
	Case 6- Right Angled Pathways only, Switched Positioning of Fresh and Waste Mains						
P2S2	0	18.13	9.94	11.58	0	2.76	0
P2S1	0	0	0	1.52	3.77	0	0
P3S1	0	0	0	5.56	1.74	2.89	0
P6S2	0	0	0	0	0	4.29	0
P6S1	0	0	0	0	0	2.10	3.32
P4S1	0	14.17	34.81	0	0	0	2.42
Fresh	14.82	1.66	2.38	4.16	0	0	0

Table 12. Continued

Pressure Drop (bar)	P1D1	P1D2	P3D1	P5D1	P5D2	P4D1	Waste
	Case 7-Diagonally Integrated Pathways, Original Positioning of Fresh and Waste Mains						
P2S2	0	16.39	9.05	10.20	0	2.68	0
P2S1	0	0	0	1.34	3.40	0	0
P3S1	0	0	0	5.05	1.61	2.69	0
P6S2	0	0	0	0	0	3.83	0
P6S1	0	0	0	0	0	1.93	4.31
P4S1	0	12.83	31.34	0	0	0	4.61
Fresh	22.39	2.64	2.18	2.81	0	0	0
Case 8-Diagonally Integrated Pathways, Switched Positioning of Fresh and Waste Mains							
P2S2	0	16.39	9.05	10.20	0	2.68	0
P2S1	0	0	0	1.34	3.40	0	0
P3S1	0	0	0	5.05	1.61	2.69	0
P6S2	0	0	0	0	0	3.83	0
P6S1	0	0	0	0	0	1.93	3.09
P4S1	0	12.83	31.34	0	0	0	2.08
Fresh	13.83	1.59	2.15	3.64	0	0	0

II.8.3 Interplant Network Cost Comparison

The optimal costs, for implementing direct recycle, in addition to the total fresh costs, the total annualized piping and fresh costs, as well as the required pumping costs which in turn consider pressure adjustment costs (i.e, annualized pumping capital costs and yearly operating costs) according the pressure drop values provided in Tables 8 and 12, are presented in Table 13.

Table 13. Summary of total costs obtained for all cases

	Case 1	Case 2	Case 3	Case 4
Total Piping Costs ($)	11,538,681	10,182,951	10,516,101	9,313,791
Total Fresh Costs ($/yr)	227,760	227,760	227,760	227,760
Annualized Piping + Fresh Costs ($/yr)	804,694	736,908	753,565	693,450
Total Pumping Costs ($/yr)	118,349	91,811	109,310	84,937
	Case 5	**Case 6**	**Case 7**	**Case 8**
Total Piping Costs ($)	12,763,004	11,211,408	11,668,973	10,219,886
Total Fresh Costs ($/yr)	258,328	258,328	258,328	258,328
Annualized Piping + Fresh Costs ($/yr)	896,478	818,898	841,776	769,322
Total Pumping Costs ($/yr)	122,950	104,538	113,416	95,098

Carbon steel Schedule 80 welded pipes were assumed (having cost parameters a=696.58 and b=1.215 (Peters, Timmerhaus et al. 2003)). A freshwater cost (C^{FRESH}) of 0.13 $/ton was used (Rubio Castro et al. 2011), in addition to a total of 8760 hr/yr operating hours (H_y), and an annualized factor γ= 0.05. Moreover, an 80% efficiency (η) in the pump calculations were assumed, with a total power cost of 0.05 $/kWh. Figure 8 illustrates optimum cost comparison obtained for both the single and multiple contaminant scenario cases.

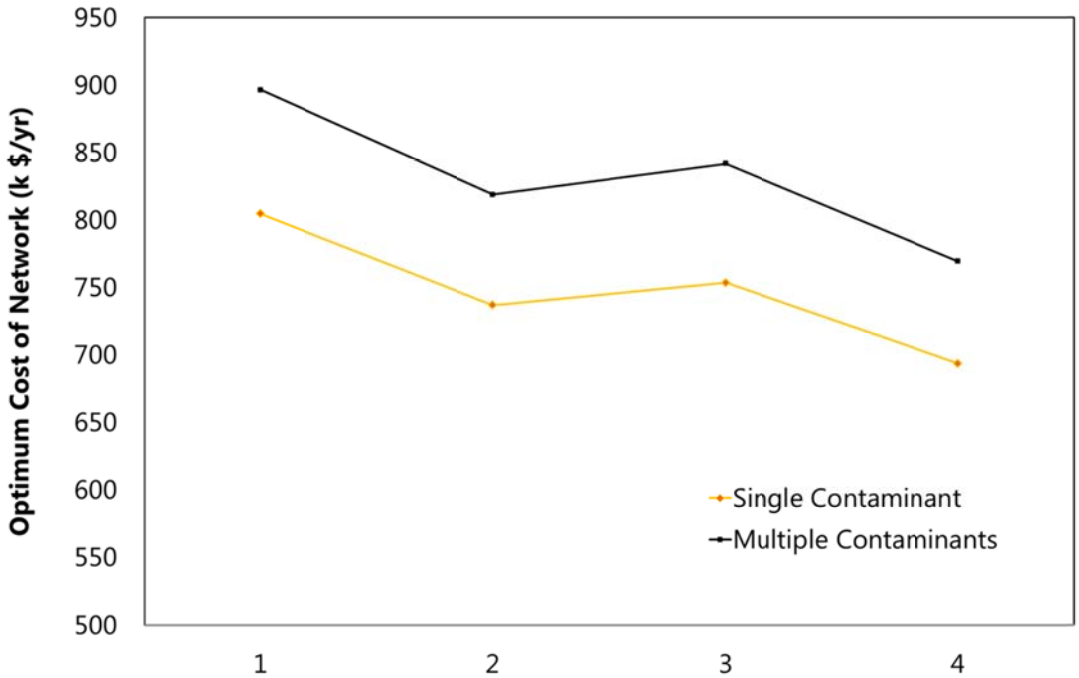


Figure 8. Optimum network cost comparison based on contaminant information for all cases

The results show that Type 2 connectivity allow less expensive piping options to be implemented in most of the cases that have been examined. Moreover, the results indicate that the positions of fresh and waste streams as in Figure 7, are more effective in terms of piping costs due to the distances extracted, compared to Figure 6. It is also evident that multiple contaminant information is associated with higher optimum cost figures. Moreover, Case 4 in which the fresh and waste mains positioned were altered, that allowed diagonally integrated pathways for piping connectivity (i.e. Type 2) yield the best results for interplant water network designs. Figure 9 illustrates the best case solution amongst all single contaminant scenarios, and Figure 10 shows the best solution amongst all multiple contaminant cases.

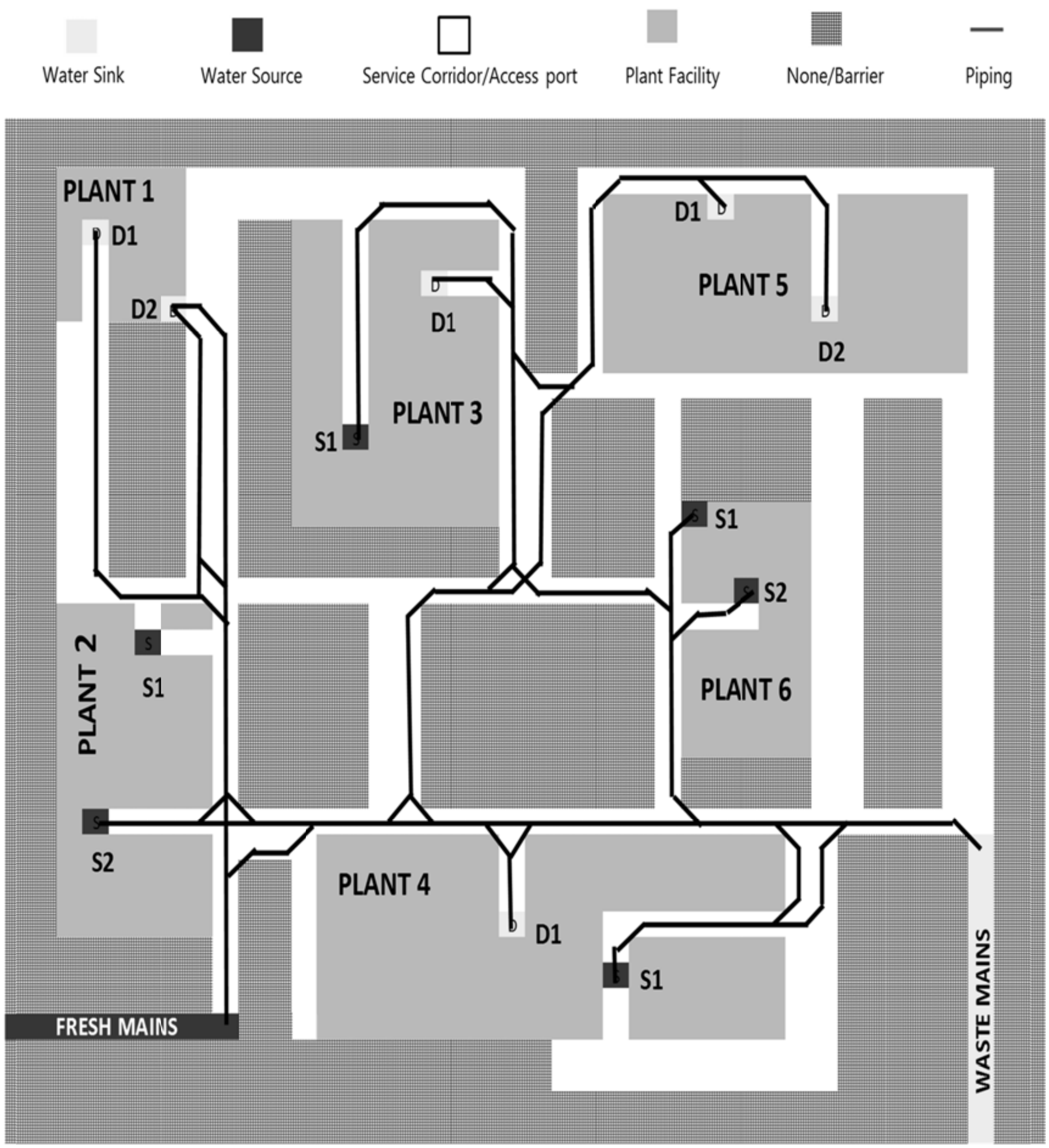


Figure 9. Best solution amongst all single contaminant cases (Case 4)

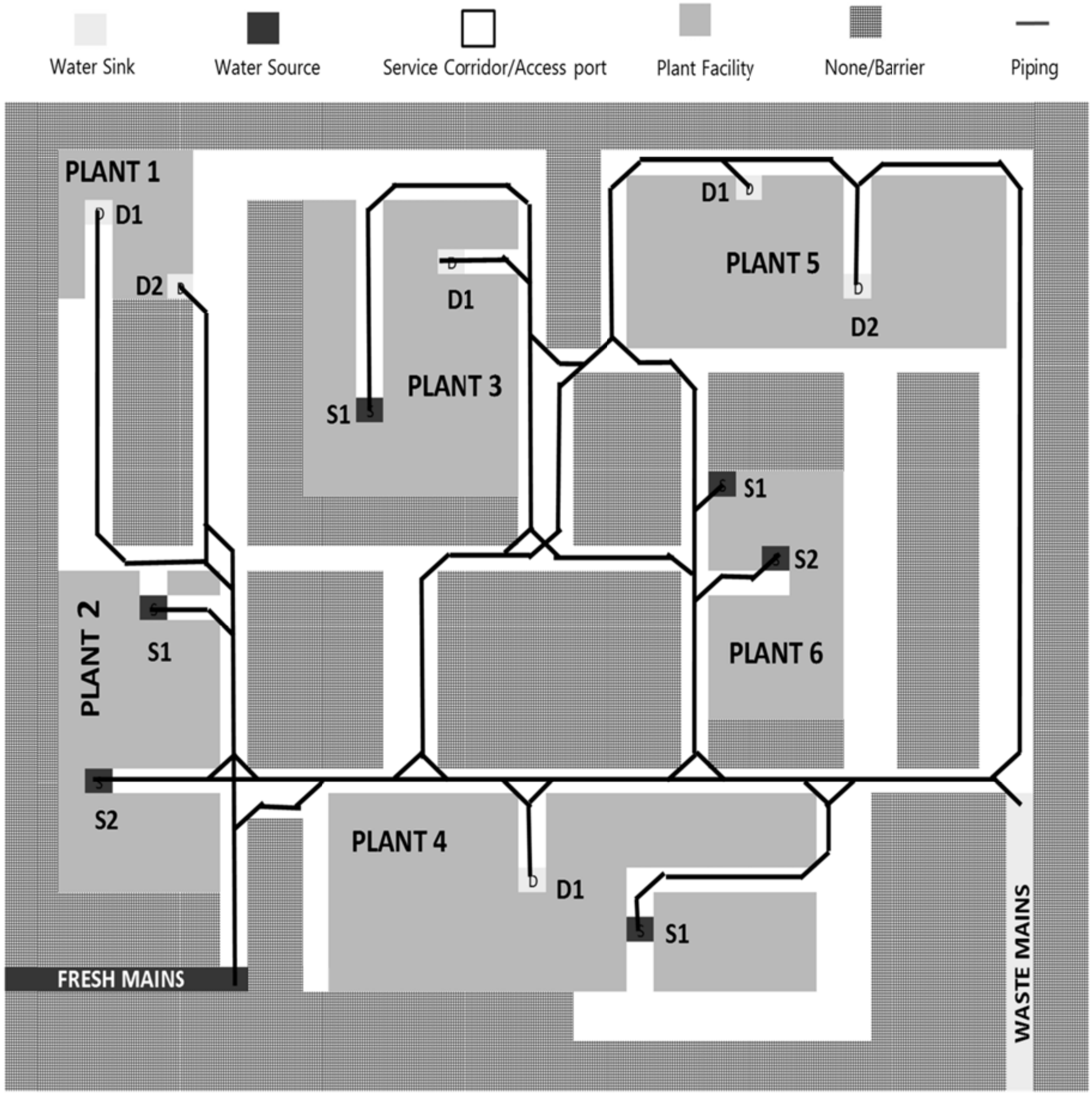


Figure 10. Best solution amongst all multiple contaminant cases (Case 4)

II.8.4 Un-integrated vs. Integrated Water Consumption Comparison

Comparing the initial situation of having all plants within the industrial city operating individually, each managing its fresh and waste separately, to the modified setting after implementing global water integration direct recycling strategies, abundant water savings can be achieved, for both the single and multiple contaminant scenarios. A comparison of the respective use of fresh and wastewater in each plant is provided in Table 14 for the various cases.

Table 14. Single vs. Multiple Contaminant Water Savings

	Initial Case, Single Contaminant	**Integrated Solution- Single Contaminant**	**Initial Case, Multiple Contaminants**	**Integrated Solution - Multiple Contaminants**
Plant 1				
FRESH	200 t/h	160 t/h	200 t/h	160 t/h
WASTE	0 t/h	0 t/h	0 t/h	0 t/h
Plant 2				
FRESH	0 t/h	0 t/h	0 t/h	0 t/h
WASTE	200 t/h	0 t/h	200 t/h	0 t/h
Plant 3				
FRESH	80 t/h	40 t/h	80 t/h	40 t/h
WASTE	140 kg/h	0 t/h	140 kg/h	0 t/h
Plant 4				
FRESH	95 t/h (DR*)	0 t/h	195 t/h	0 t/h
WASTE	0 t/h (DR*)	0 t/h	100 t/h	60 t/h
Plant 5				
FRESH	220 t/h	0 t/h	220 t/h	26.84 t/h
WASTE	0 t/h	0 t/h	0 t/h	0 t/h
Plant 6				
FRESH	0 t/h	0 t/h	0 t/h	0 t/h
WASTE	275 t/h	220 t/h	275 t/h	186.8 t/h
TOTAL FRESH	595 t/h	200 t/h	695 t/h	226.8 t/h
TOTAL WASTE	615 t/h	220 t/h	715 t/h	246.8 t/h

*Implementing direct recycle within plant

The initial case involves no integration amongst plants, with freshwater being used in all sinks, and wastewater from all sources going to waste. A total of 595 t/h of fresh and 615 t/h of waste found using single contaminant data, and 695 t/h of fresh and 715 t/h of waste found using multiple contaminant data. This is because water consumption in plant 4 can be reduced by 100 t/h, when incorporating an in-process direct recycling for the single contaminant case, since the concentration limits for the sink involved is not violated, unlike the multiple contaminant scenario. Implementing water integration amongst the various plants allows many instances of water-saving opportunities. For example, the single contaminant scenarios involves both fresh and waste elimination from plant 4, in addition to completely cutting off freshwater consumption in plant 5 and wastewater discharge in plant 2. Moreover, the freshwater consumption in plants 1 and 3 were reduced. Water-savings for all multiple contaminant cases were not as much as the former cases, but nevertheless much fresh and waste reduction were achieved. For instance, wastewater discharge in plant 2 was completely eliminated, and freshwater utilization in plants 1, 3 and 5 were decreased.

II.9. Conclusions

This work involves the use of direct recycling water integration strategies for achieving a macroscopic optimization framework of water networks within an industrial city plot. This approach is more conventionally known as “direct integration”. A simple representation that can capture an industrial city layout has been developed, which would allow the exploration of any infrastructure setting for water integration possibilities. The representation takes into consideration industrial city corridors, access ports, as well as obstructed areas, in addition to the ability of specifying all water source and sink locations. This in turn could effectively be used for obtaining the shortest paths that allow source-sink mapping. Dijkistra's algorithm has been utilized to extract all shortest path distances, given a set of sources and water destinations within the plot. A case study has been carried out, assuming two types of connectivity for an industrial city example, as a demonstration. It was shown that effective freshwater savings and waste minimization via direct recycling can be achieved. Moreover, it was found the location of fresh and waste mains affect optimal piping costs, as each case was associated with different sets of distance data. As a result, it can be concluded that the industrial city layout, as well as how individual plants are arranged would significantly affect the water integration options available.

Accounting for "indirect integration" opportunities by introducing partial treatment options for wastewater streams before re-use, at the expense of having to invest in treatment facility infrastructure, will be the subject of future studies. The approach introduced in this work can also be helpful when conducting macroscopic energy integration studies (Stijepovic and Linke 2011; Stijepovic et al. 2012). Other potential areas for future work can also involve investigating situations in which individual plants are owned by different companies, and the various opportunities that could possibly lead to mutual benefits amongst the plants, based on game theory principles have been reported in earlier studies (Chew et al. 2009).

CHAPTER III

A SYNTHESIS APPROACH FOR INDUSTRIAL CITY WATER REUSE NETWORKS CONSIDERING CENTRAL AND DISTRIBUTED TREATMENT SYSTEMS*

This work introduces a representation of spatial aspects in water integration problems within industrial zones, which can be applied to problems involving any type of water integration strategies. The representation and takes into consideration the respective plant locations, and any barriers that exist in between. Moreover, industrial city corridors that are allocated for water transport have also been accounted for. This allows effective water integration and matching amongst available water streams using a spatially constrained approach that utilizes the shortest path options available. The proposed representation has been illustrated using direct recycling integration strategies, which in turn are commonly recognized to employ the simplest techniques for water integration, as a first instance. A case study involving several water using and producing processes that belong to a group of plants all operating in a common industrial zone has been carried out as a demonstration, and several different scenarios have been studied. In doing so, cost effective water network designs that involve attractive wastewater reuse schemes amongst adjacent and nearby processing facilities have been identified, while considering the spatial constraints of water transport.

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III.1. Introduction

Excessive utilization of freshwater resources in industrial sectors negatively affects water stressed regions (Jhansi and Mishra 2013). Therefore, the application of effective water management strategies within industrial cities is undoubtedly an important aspect to consider for the sustainability of industrial operations. In addition to the need for reducing stress on expensive fresh water resources, industries are challenged with increasingly strict environmental regulations on wastewater discharge, due to its adverse impacts on natural ecosystems (Englert, Zubrod et al. 2013). Reductions in fresh water use and discharge flows are typically realized through the re-processing and reuse of wastewater streams (Jhansi and Mishra 2013). Chen and Chen (2014) studied various factors affecting the reuse of reclaimed water, and proposed a mathematical model to analyze the extent to which effluent should be reclaimed for industrial use. Moreover, water integration within processing facilities has been the subject of numerous foregoing studies, as a means of effectively reducing industrial water footprints. The reliability of many of the existing methodologies in terms of achieving water integration has instigated very promising advances in the field, as well as many significant contributions. Generally speaking, the design of water networks was initially carried out for stand-alone processes in numerous studies, either using graphical or mathematical programming techniques. For instance, early contributions in the field of water integration were by Wang and Smith (1994a,1994b) in which they introduced a graphical targeting approach that ultimately minimizes freshwater consumption, as well as wastewater discharge, within a process. Additionally, many methodologies that were first introduced were limited to the design of water networks involving a single contaminant only. Later on, research efforts were then extended to handle multiple contaminants. For instance, Alva-Argáez et al. (1999), optimized a water network problem involving multiple contaminants was optimized by combining water-pinch analysis techniques with mathematical programming tools.

The design of water networks has also been applied to problems involving multiple processing facilities, in the context of achieving Industrial Ecology (Ehrenfeld and Gertler, 1997). Eco-Industrial Parks were introduced as clusters of processes that efficiently share common resources (Côté and Hall 1995). Lowe (1997) explored resource recovery facilities and possible strategies for creating resource and by-product exchanges, amongst a cluster of neighboring companies. Soon after, the design of water exchange networks in Eco-industrial parks (EIPs) became the subject of many research contributions. Various methods such as mathematical programming, pinch analysis, as well as game theory procedures have been utilized for the design of water exchange networks in EIPs. Yoo et al. (2007) utilized a pinch analysis technique for wastewater minimization, as well as explored simultaneous water-energy minimization, and energy-pinch design in eco-industrial parks (EIP). Kim and Lee (2007) addressed Pareto optimal networks, based on the principal of sharing resources amongst participating entities. Liao et al. (2007) developed an MILP model for designing flexible water networks that can be applied to problems involving fixed contaminant and fixed flow operations, while accounting for the number of cross plant interconnections in the water minimization problem. Foo (2008) targeted plant-wide integration using numerical tools for water cascade analysis. Lovelady and El-Halwagi (2009) introduced a mathematical formulation for the design of EIP water networks based on a source-interception-sink-representation. Chew et al. (2008) proposed a centralized hub topology used for collecting and redistributing water, for Inter-plant Water Integration (IPWI).

Later on, Chew and Foo (2009) formulated a linear programming model that was used for automated targeting of interplant water networks, based on pinch analysis techniques. Chew et al. (2009) also developed a game theory scheme for designing IPWI networks, by assessing various interactions between participating companies. Lim and Park (2009) conducted environmental and economic feasibility studies to demonstrate benefits from industrial symbiosis, and developed interfactory and intrafactory water network systems. Kim et al. (2010) introduced a systematic approach for optimizing utility networks in an industrial complex, using a multi-period Mixed Integer Linear Programming (MILP) model. Rubio-Castro et al. (2010) modeled wastewater reuse among different industries, for which an optimal selection of treatment units was determined, satisfying all the process and environmental regulations for waste discharges. Later on, Chew et al. (2010a, 2010b) presented a new algorithm for the design of interplant resource conservation networks, by targeting minimum freshwater use and wastewater discharge. Aviso et al. (2010a, 2010b) presented models for optimizing water and wastewater reuse amongst independent processing facilities in an EIP, through fuzzy mathematical programming. Taskhiri et al. (2011) developed an MILP model for interplant water networks that accounts for environmental impacts of water use, energy consumption, and capital goods within an EIP, by minimizing the total emergy of the network. Rubio-Castro et al. (2011) proposed a global optimal formulation to design water integration networks in eco-industrial parks, in which a superstructure that accounts for wastewater reuse both within the plant, as well as amongst different plants was utilized. Rubio-Castro et al. (2012) then examined ways of retrofitting several single-plant water networks into an eco-industrial park using a MINLP model, by accounting for both intra-plant and inter-plant decisions. Boix et al. (2012) developed a methodology to design industrial water networks using a multi-objective optimization strategy, in which a Mixed-Integer Linear Programming problem (MILP) was proposed, based on the necessary conditions of optimality defined by Savelski and Bagajewicz (2000).

Following this work, Montastruc et al., (2013) formulated a triobjective MILP, in which the fresh water flows, regenerated water flows, and the number of connections were minimized. Moreover, the flexibility of the water supply system for an EIP of any size was also investigated. Lee et al. (2013a) developed a mathematical optimization model for inter-plant water network synthesis, using a two-stage approach in which the individual processing units operate in a mix of both continuous and batch modes. More recently, Alnouri et al. (2014a) investigated the design of interplant water networks via direct water reuse, whilst considering spatial aspects within industrial city layouts. Moreover, Alnouri et al. (2014b) also addressed interconnectivity options in water network designs by introducing pipeline merging opportunities. Soon afterwards, Bishnu et al. (2014) introduced a multi-period approach for the design of interplant water networks. It is good to note that many of the methods developed aim to improve the overall performance of real eco-industrial park applications. For instance, Tian et al. (2014) assess the economic and environmental performance several existing eco-industrial parks, based on the quantity of energy and fresh water consumption, wastewater and solid waste generation. Their work also highlights the importance of effectively developing interplant water network methodologies that could then be applied to real case scenarios.

III.2. Synthesis Problem

As discussed in the previous section, many available water integration methodologies either use pinch analysis techniques, mathematical programming tools, or a combination of both to target the minimum freshwater usage and wastewater discharges in water network synthesis problems. The problems usually range from those involving direct water recycle, to problems that involve introducing wastewater treatment before reuse, via intermediate treatment interception units. Despite all research efforts that have been made so far, an interplant water integration methodology that explicitly addresses all the different options available for the placement of intermediate water treatment interception options, has not been addressed as of yet. Even though most interplant water network studies that have been previously carried out do consider treatment, much of the cases that have been investigated involved introducing shared water treatment amongst an existing cluster of plants (Chew, Tan et al. 2008; Lovelady and El-Halwagi 2009; Rubio-Castro, Ponce-Ortega et al. 2010).

Some studies such as Boix at al. (2012), did compare the design of water networks within an EIP setting for with different treatment scenarios involved For instance, one of the scenarios assumed that each company owns a treatment unit, while another scenario assumed a number of shared treatment units amongst all companies. However, incorporating both company-owned and shared treatment units simultaneously into the model has not been explored in any of the studies that have been made so far. In an attempt to bridge the research gap, and due to decision-making that is often required for the placement of water treatment units amongst a cluster of processing facilities in an industrial zone, this work integrates both company-owned and shared treatment units, simultaneously. Thus, the proposed method assists in evaluating whether participating entities would benefit from a shared treatment facility that is allowed to treat wastewater from all plants, versus the case that would involve each company treating its wastewater separately before reuse, in a company owned facility. A combination of both scenarios can sometimes be attractive, depending on what plants are involved, the type of wastewater being produced, and the plant arrangement considered.

Moreover, since investigating an effective strategy for the integration of company-owned, and shared treatment units within an water network design can be carried out more effectively once a given industrial city layout is captured, this paper discusses the planning of interplant water networks through regeneration and reuse, whilst accounting for spatial problem features. The respective water allocations in between the different plants can be planned out more effectively if a spatial representation is utilized, as it facilitates the integration of available water streams based on their locations (both treated and untreated), as the problem would allow for optimal routing and allocation of flows amongst the different participants, while accounting for available city infrastructure. Therefore, this paper is an extension to our previous work (Alnouri, Linke et al. 2014a), in which we introduced a systematic approach for capturing industrial city layouts. The methodology allows plant locations, service corridors and city boundaries to be defined accordingly, and hence interactions between clusters of processing facilities can be investigated more effectively based on a provided input layout scheme. Furthermore, optimal placement strategies for water treatment units onto a given layout can also be attempted, as it would involve identifying several respective potential locations according a provided industrial city arrangement, and then selecting the best scenarios available. All treatment interception units introduced into the designs should be capable of removing unwanted pollutants in wastewater streams before being sent over to water sink locations across the city, thus located in easily accessible regions. The piping required to achieve cost-effective water integration amongst different plants was also accounted for by calculating the respective pipe lengths and diameters, in a similar manner to our previous work. The described approach has been applied by considering both direct water re-use, and wastewater treatment options in this paper. The optimization model has been formulated as a Mixed Integer Non-Linear Program (MINLP) to determine economically-effective interplant water network designs that are able to satisfy water demands, as well as wastewater discharge requirements, within a given plant cluster. Section 3 outlines the proposed water integration representation, and Section 4 presents the mathematical formulation.

III.3. Water Integration Framework with Treatment Options Introduction

The optimal design of interplant water networks within an industrial city is greatly affected by many technical and economic factors. One of the important elements that determine the economical attractiveness of interplant water integration networks is the industrial city infrastructure. Moreover, the availability of excess water/wastewater within individual plants, and the potential allocation options associated with each, also plays a key role in determining viable solutions. Hence, the arrangement of process sources and sinks within existing plants greatly influences the feasibility of source-sink water distribution options, together with their respective flow rates, as well as the pollutant specifications and/or limits. Additionally, introducing a set of wastewater treatment units, with effective pollutant removal capabilities, can help reduce freshwater supply requirements. Moreover, water treatment might also be necessary in order to meet imposed limits for pollutant concentrations in wastewater streams being discharged to the environment. Therefore, as it has been described in Section 2, this work investigates water treatment opportunities when designing interplant water networks amongst multiple processing, by taking into consideration industrial city infrastructures and cost-effective pipe arrangements. It should be pointed out that the term ‘industrial city’ refers to a cluster of processing facilities, located within geographic proximity. Implementing potential water integration options, amongst different plants located within an industrial city, can be achieved applying efficient schemes for sharing water resources. This contributes to its transformation to a form of Eco-Industrial Park (EIP),in which both treated and untreated water reuse options can be realized. The following sections describe the methodology that has been adopted.

III.3.1 Source-Interceptor-Sink Allocation

Water integration through recycle and reuse, as well as treatment and separation using interception devices were both considered possible strategies for managing wastewater. A source-interception-sink representation was utilized for embedding the following potential configurations of interest: direct wastewater re-use from source(s) to sink(s), treatment of wastewater in interception units, treated water allocation to process sink(s), freshwater utilization in process sink(s), wastewater discharge form process sink(s), treated water discharge. The various water users (Sinks) and water discharges (Sources) within the different plants need to be specified, in addition to water flow and contaminant compositions. Maximum specifications for acceptable contaminant levels in water sinks are also specified in order to ensure that pollutant levels are not exceeded. All required data is then used as input into a source-interceptor-sink allocation so as to deliver plausible options for the assignment of wastewater water streams to treatment units and/or to water users amongst the various processing facilities within the city. The main objective is to minimize the cost of the water network design, whilst considering water recycle, separation and treatment strategies. In doing so, two different treatment strategies were accounted for:

1. Decentralized Treatment "On-site Treatment": this option involves on-site treatment arrangements in which only wastewater from within the plant itself is handled. These treatment units are located within the plant boundaries, and no wastewater is allowed to be received for treatment in the facility except wastewater sources that originate from the same plant itself. Moreover, no wastewater from the plant involved is allowed to be sent for treatment to another on-site treatment facility that is within the borders of an adjacent/nearby plant.

2. Centralized Treatment "Shared Treatment": this option involves off-site collective treatment arrangements in which wastewater streams from within the entire city are handled. All centralized treatment units are located within common infrastructure boundaries, which would ultimately allow processing wastewater from sources that originate from any of the plants within the city.

Figure 11 illustrates the adopted water treatment concept and stream distribution options that are associated with each of the central and decentral treatment options. All treated water streams are allowed to be sent to any of the water users within the industrial city boundaries, as required, regardless of the processing facility that the respective sinks are located in.

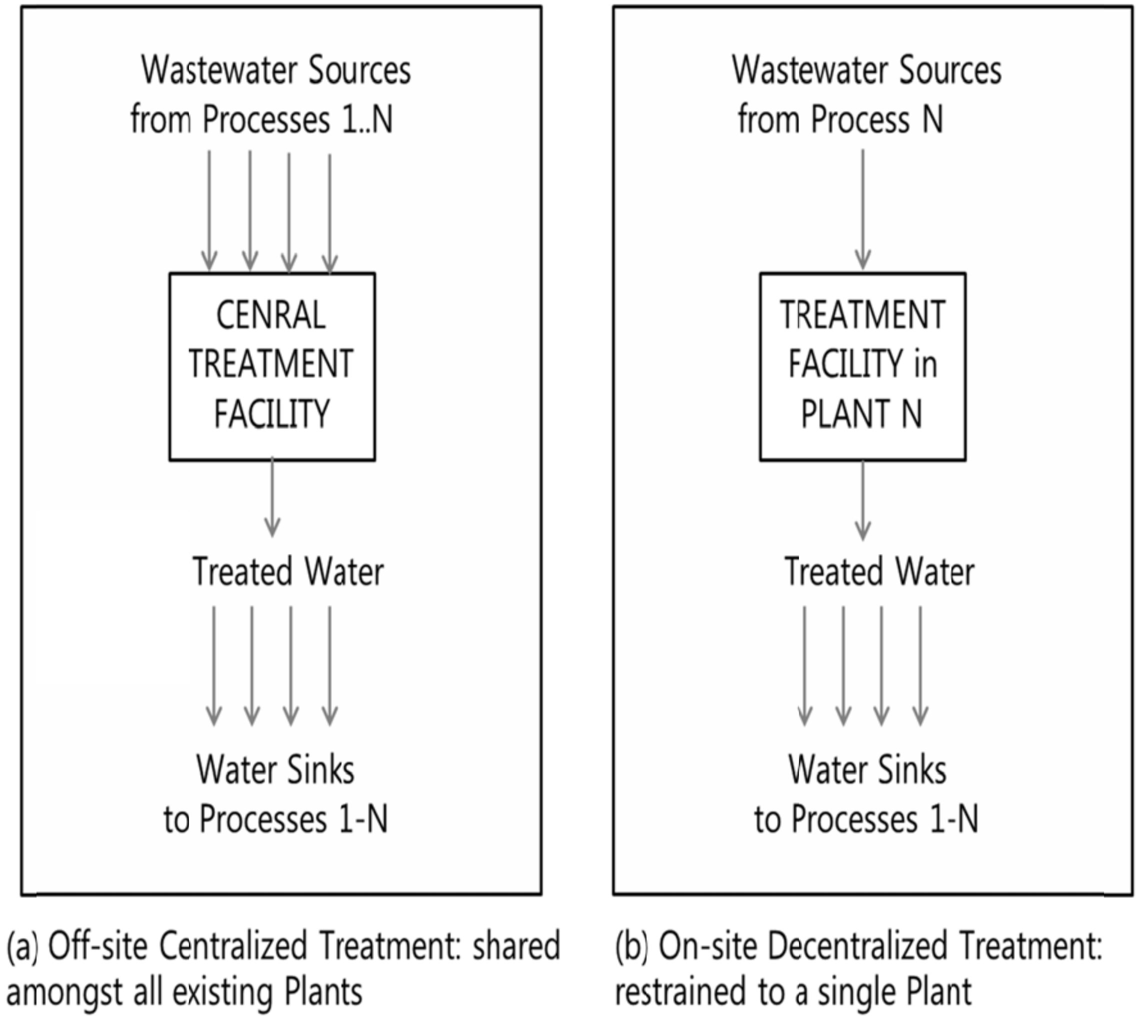

Figure 11. Wastewater treatment options illustrated (a) centralized treatment scenario and (b) decentralized treatment scenario

III.3.2 Water Piping: Routing and Connectivity Planning

In addition to determining an optimal source-interception-sink allocation of streams, a water transportation problem is also formulated in order to effectively plan the routing and piping options for a cost-effective water network design. As described in our previous work (Alnouri, Linke et al. 2014a), information on water source and sink locations within individual processing facilities are first identified, for which routing to and from can be one of the feasible options. Moreover, service corridors as well as access points associated with water sources and sinks within the individual plants are also identified. This work also considers treatment options; therefore, water treatment locations (both on-site and centralized) need to be specified. The corresponding routing to and from each of the treatment units are additionally incorporated as possible connectivity options. This overall planning model for piping meshes would ultimately include all the different possible stream allocations: (1) source-to-sink; (2) source-to-interceptor; (3) interceptor-to-sink; (4) fresh-to-sink; (5) source-to-waste; and (6) interceptor-to-waste. For each of the connectivity categories described, shortest routing can be extracted, based on an input layout scheme for the industrial city. The procedure was carried in a similar manner to our previous work considering direct reuse without treatment (Alnouri, Linke et al. 2014a), and is summarized in the following steps: (1) input industrial city layout; (2) identify corresponding active and inactive regions; (3) locate source and destination points; (4) shortest routing extraction for piping connectivity options according to desired constraints. Figure 12 illustrates active and inactive region categories for Step 2, having introduced treatment options. All active regions are utilized to determine routing options between the sources, sinks and treatment interception locations. It can be noted that all treatment unit locations (both on-site and off-site) are associated with source and destination cells, which are respectively designated to receive process wastewater, and provide regenerated water after treatment. Effective routing between source and destination cells for step 4 can be executed using any desired algorithm that achieves shortest path results (Damak 2010). In this paper, Dijkstra's Algorithm has been employed (Dijkstra 1959). Moreover, two different connectivity scenarios for the piping were assumed. Type 1 only allows right-angles within the routes extracted, while Type 2 enables diagonal node-to-node linking (Alnouri, Linke et al. 2014a). Thus, two different connectivity mesh scenarios for piping were utilized. A counting function that provides the number of diagonal bends and 90^0 elbows in each of the routes extracted was employed. This information was necessary to compute the pressure drops in the network. Moreover, this work involves the construction of a separate pipe for each of the allocations identified, and standard pipe diameters sizes and material costs were employed in the calculations.

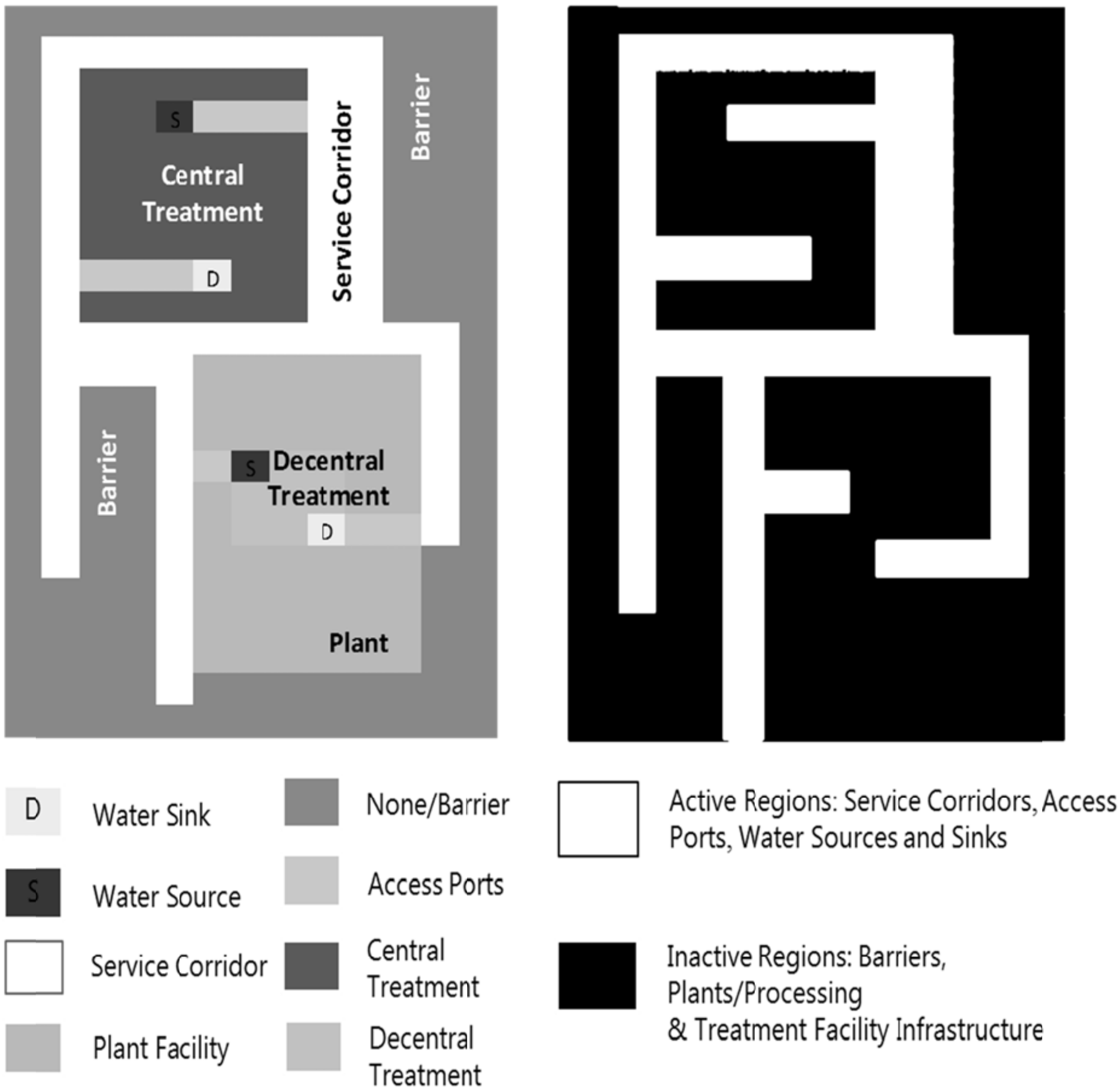

Figure 12. Active and Inactive regions categories illustrated, together with an input prototype with water treatment introduced

III.4. Problem Statement & Mathematical Formulation

It is required to determine the optimal design of an interplant water network given an industrial city scheme encompassing multiple plants P, each containing a set of water sources SU_p and a set of water sinks SN_p with specified flow rates and pollutant concentration specifications and/or limits for a set of contaminants C. In this problem we are also given a set of on-site decentral water treatment interceptors R with specified pollutant removal capabilities. Moreover, several centralized water treatment interceptors that are shared amongst all plants within the industrial city with respective locations S are given, each associated with a number of different treatment options T with certain pollutant removal capacities. Furthermore, a set of fresh water supply options L is given, with different costs and pollutant concentrations. It is required to develop a strategy for the optimal water reuse, recycle and treatment across individual processes, in the form of a cost-effective water network designs that would ultimately allow for economical global water resource conservation across the industrial city, whilst considering environmental discharge regulations that are imposed on unused wastewater streams.

III.4.1 Model Formulation

The objective function consists of the minimization of a total annualized cost, which includes the costs of fresh water, wastewater treatment, piping and waste disposal costs as described by Equation (37) below:

$$Minimize.\;\; FC + TC + PC + WC \tag{37}$$

The piping expenses utilize costs per m^3 of length that are calculated according to the diameters of the various piping segments:

$$\sum_{p,p' \in P} \sum_{i \in SU_p} \sum_{j \in SN_p} a\left(DI_{ip,jp'}\right)^b L_{ipjp'} + \sum_{p \in P} \sum_{i \in SU_p} a\left(DI_{ip}\right)^b L_{ip} + \sum_{l \in L} \sum_{p \in P} \sum_{j \in SN_p} a\left(DI_{l,jp}\right)^b L_{l,jp} + \sum_{p \in P} \sum_{r \in R} \sum_{i \in SU_p} a\left(DI_{ip,rp}\right)^b L_{ip,rp} + \sum_{p \in P} \sum_{i \in SU_p} \sum_{s \in S} \sum_{t \in T} a\left(DI_{ip,st}\right)^b L_{ip,st} + \sum_{p \in P} \sum_{r \in R} \sum_{j \in SN_p} a\left(DI_{rp,jp}\right)^b L_{rp,jp} + \sum_{p \in P} \sum_{j \in SN_p} \sum_{s \in S} \sum_{t \in T} a\left(DI_{st,jp}\right)^b L_{st,jp} + \sum_{p \in P} \sum_{r \in R} a\left(DI_{rp}\right)^b L_{rp} + \sum_{s \in S} \sum_{t \in T} a(DI_{st})^b L_{st} \quad (38)$$

Freshwater costs are based on the required flowrates, using costs of freshwater for the different types available, as well as the operating hours per year:

$$FC = H_y \sum_{l \in L} \sum_{p \in P} \sum_{j \in SN_p} F_{l,jp} C_l^{FRESH} \quad (39)$$

Wastewater discharge costs refer to the costs of disposing all unutilized wastewater streams through a collective waste mains. Options available for wastewater disposal depend on the policies and regulations applicable to the industrial city being considered, as well as the costs associated per flow discharged. In this study, wastewater discharge costs only involve the extra handling costs via piping and pumping required for disposal, since wastewater treatment costs have already been accounted for in the central/decentral treatment systems. The costs were based on the obtained discharge flowrates, and the operating hours per year:

$$WC = H_y C^{WASTE} D^{total} \tag{40}$$

Total water treatment costs involve summation terms for both central and decentral types, and each includes fixed and operating costing terms.

$$TC = K_F \sum_{p \in P} \sum_{r \in R} \left(T_{rp}^{total}\right)^{\alpha} C_{rp}^{INV} + K_F \sum_{s \in S} \sum_{t \in T} \left(T_{st}^{total}\right)^{\alpha} C_{st}^{INV}$$
$$+ H_y \sum_{p \in P} \sum_{r \in R} \sum_{c \in C} T_{rp}^{total} x_{c,rp}^{REM} C_{rp}^{REM} + \sum_{s \in S} \sum_{t \in T} \sum_{c \in C} T_{st}^{total} x_{c,st}^{REM} C_{st}^{REM} \tag{41}$$

The model formulation includes a set of mass balances for each of the sources, sinks, and interceptors in the system as described by Equations (42)-(44) below. Note that a comma was used to separate a connection's starting point, and endpoint in all variables that have been defined. Moreover, a comma was also employed to indicate component information. The summation of source-to-sink, source-to-interceptor (both central and decentral), and source-to-waste flowrates must equal the total mass balance for the specified process water source flowrate.

$$\sum_{p,p' \in P} \sum_{j \in SN_p} M_{ip,jp'} + \sum_{p \in P} \sum_{r \in R} T_{ip,rp} + \sum_{s \in S} \sum_{t \in T} T_{ip,st} + D_{ip} = W_{ip}$$
$$\forall p \in P\ ;\ \ \forall i \in SU_p \tag{42}$$

The summation of source-to-sink, interceptor-to-sink (both central and decentral), and fresh-to-sink flowrates must equal the total mass balance for the specified process water sink flowrate.

$$\sum_{p,p' \in P} \sum_{i \in SU_p} M_{ip,jp'} + \sum_{p \in P} \sum_{r \in R} T_{rp,jp} + \sum_{s \in S} \sum_{t \in T} T_{st,jp} + \sum_{l \in L} F_{l,jp} = G_{jp}$$

$\forall p \in P\ ;\ \ \forall j \in SN_p$ (43)

The summation of source-to-sink, interceptor-to-sink (both central and decentral), and fresh-to-sink flowrates each multiplied by their respective pollutant contaminants must equal the total flow balance specified process water sink flowrate multiplied by the respective pollutant concentration.

$$\sum_{p,p' \in P} \sum_{i \in SU_p} M_{ip,jp'} x_{c,ip}^{Source} + \sum_{p \in P} \sum_{r \in R} T_{rp,jp}\, x_{c,rp}^{out} + \sum_{s \in S} \sum_{t \in T} T_{st,jp}\, x_{c,st}^{out} + \sum_{l \in L} F_{l,jp}\, x_{c,l}^{FRESH} = G_{jp} z_{cjp}^{in}$$

$\forall p \in P\ ;\ \ \forall j \in SN_p\ ;\ \forall c \in C$ (44)

Moreover, each contaminant concentration must be within the specified limits for acceptable pollutant concentration within process water sinks, (Alnouri, Linke et al. 2014a).

$$z_{c,jp}^{min} \le z_{c,jp}^{in} \le z_{c,jp}^{max}$$

$\forall p \in P\ ;\ \ \forall j \in SN_p\ ;\ \forall c \in C$ (45)

All treatment options utilized in the problem represent a sequence of treatment stages, with specified removal ratios. Moreover, multiple centralized treatment locations and treatment options were allowed in the case of centralized treatment. In order to choose the best treatment option for a corresponding location, only one option was allowed for each. Therefore, Equation 46 below ensures a consistent selection process, amongst all potential centralized treatment options:

$\sum_{t \in T} y_{st} \le 1 \quad \forall s \in S$ (46)

Equations (47) and (48) were also utilized to ensure that all corresponding flows are in consistency with the treatment options selected.

$$y_{st}L \leq T_{ip,st} \leq y_{st}U$$

$$\forall p \in P\ ;\ \ \forall i \in SU_p\ ;\ \forall s \in S\ ; \forall t \in T\ ; \forall y_{st} \in \{0,1\} \tag{47}$$

$$y_{st}L \leq T_{st,jp} \leq y_{st}U$$

$$\forall p \in P\ ;\ \ \forall j \in SN_p\ ;\ \forall s \in S\ ; \forall t \in T\ ; \forall y_{st} \in \{0,1\} \tag{48}$$

Total interceptor flowrates (both central and decentral) must be equal to the summation of all source-to-interceptor flows into the respective units.

$$T_{rp}^{total} = \sum_{p \in P} \sum_{i \in SU_p} T_{ip,rp}$$

$$\forall p \in P\ ;\ \ \forall r \in R \tag{49}$$

$$T_{st}^{total} = \sum_{p \in P} \sum_{i \in SU_p} T_{ip,st}$$

$$\forall s \in S\ ;\ \ \forall t \in T \tag{50}$$

Total interceptor flowrates (both central and decentral) multiplied by their respective inlet pollutant compositions must be equal to the summation of all source-to-interceptor flows multiplied by their corresponding pollutant concentrations.

$$T_{rp}^{total} x_{c,rp}^{in} = \sum_{p \in P} \sum_{i \in SU_p} T_{ip,rp}\ x_{c,ip}^{Source}$$

$$\forall p \in P\ ;\ \ \forall r \in R\ \ ;\ c \in C \tag{51}$$

$$T_{st}^{total} x_{c,st}^{in} = \sum_{p \in P} \sum_{i \in SU_p} T_{ip,st}\ x_{c,ip}^{Source}$$

$$\forall s \in S\ ;\ \ \forall t \in T\ ;\ \ c \in C \tag{52}$$

Moreover, total outlet interceptor flowrates (both central and decentral) must be equal to the summation of all interceptor-to-sink flows, and interceptor-to-waste flows.

$$T_{rp}^{total} = \sum_{p\in P} \sum_{j\in SN_p} T_{rp,jp} + D_{rp}$$

$$\forall p \in P\ ;\ \ \forall r \in R \tag{53}$$

$$T_{st}^{total} = \sum_{p\in P} \sum_{j\in SN_p} T_{st,jp} + D_{st}$$

$$\forall s \in S\ ;\ \forall t \in T \tag{54}$$

The model has been made capable of including a separate removal ratio per treatment technology, for every pollutant considered in the problem. Therefore, each treatment technology is associated with several removal ratios, one for each pollutant involved. If a treatment technology is capable of removing a certain pollutant more effectively than another, the respective removal ratio associated with each pollutant can be assigned as appropriate. As a result, wastewater treatment technologies are selected according to the efficiency that is required to be available, so as to achieve effective removal per pollutant involved. All outlet pollutant concentrations from each treatment unit (both central and decentral) were calculated according to the specified pollutant removal ratios, and the inlet pollutant concentration into the interceptor, according to Equations (19) and (20). Additionally, the amount of pollutant removed was calculated based on the difference between inlet and outlet interceptor pollutant concentrations, as given by Equations (21) and (22) below:

$$x_{c,rp}^{out} = x_{c,rp}^{in}\left(1 - RR_{c,rp}\right) \quad \forall p \in P\ ;\ \ \forall r \in R\ ;\ \forall c \in C \tag{55}$$

$$x_{c,st}^{out} = x_{c,st}^{in}\left(1 - RR_{c,st}\right) \quad \forall s \in S\,; \;\; \forall t \in T; \;\; \forall c \in C \tag{56}$$

$$x_{c,rp}^{REM} = x_{c,rp}^{in} - \; x_{c,rp}^{out} \quad \forall p \in P\,; \;\; \forall r \in R\,; \forall c \in C \tag{57}$$

$$x_{c,st}^{REM} = x_{c,st}^{in} - \; x_{c,st}^{out} \quad\quad \forall s \in S\,; \;\; \forall t \in T\,; \;\; \forall c \in C \tag{58}$$

Combining equations (13)-(16), (19) and (20) yields an alternative form of Equation (8), provided by Equation (23) below, in which $x_{c,ip}^{Source}, RR_{c,rp}$ & $RR_{c,st}$ are all known parameters.

$$\sum_{p,p\prime\in P}\sum_{i\in SU_p} M_{ip,jp\prime} x_{c,ip}^{Source} + \sum_{p\in P}\sum_{r\in R} T_{rp,jp} \sum_{p\in P}\sum_{r\in R}\sum_{i\in SU_p} f_{ip,rp}\, x_{c,ip}^{Source}\left(1 - RR_{c,rp}\right)$$
$$+ \sum_{s\in S}\sum_{t\in T} T_{st,jp} \sum_{s\in S}\sum_{t\in T}\sum_{i\in SU_p} f_{ip,st}\, x_{c,ip}^{Source}\left(1 - RR_{c,st}\right) + \sum_{l\in L} F_{l,jp}\, x_{c,l}^{FRESH}$$
$$= G_{jp} z_{cjp}^{in}$$

$$\forall p \in P\,; \;\; \forall j \in SN_p\,; \forall c \in C \tag{59}$$

In Equation (59), $f_{ip,rp}$& $f_{ip,st}$ represent two split fraction variables. The former corresponds to the flow fractions from all water sources that are fed into decentralized treatment units, while the latter corresponds to the flow fractions from all water sources that are fed into centralized treatment. Hence, Equations (60)-(63) were also required to ensure that the corresponding fraction values remain in the 0-1 range, as well as satisfy the mass balances into each of the treatment units, respectively.

$$0 \le f_{ip,rp} \le 1$$

$$\forall p \in P\,; \;\; \forall i \in SU_p\,; \forall r \in R \tag{60}$$

$$0 \le f_{ip,st} \le 1$$

$$\forall p \in P \; ; \; \forall i \in SU_p \; ; \forall s \in S ; \; \forall t \in T \tag{61}$$

$$\sum_{p \in P} \sum_{i \in SU_p} f_{ip,rp} \, x_{c,ip}^{Source} = x_{c,rp}^{in}$$

$$\forall p \in P \; ; \; \forall r \in R \; ; \; c \in C \tag{62}$$

$$\sum_{p \in P} \sum_{i \in SU_p} f_{ip,st} \, x_{c,ip}^{Source} = x_{c,st}^{in}$$

$$\forall s \in S \; ; \; \forall t \in T \; ; \; c \in C \tag{63}$$

The total discharge flowrates were found by summing up the flows from source-to-waste, and interceptor-to waste, as follows:

$$D^{total} = \sum_{p \in P} \sum_{i \in SU_p} D_{ip} + \sum_{p \in P} \sum_{r \in R} D_{rp} + \sum_{s \in S} \sum_{t \in T} D_{st} \tag{64}$$

$$D^{total} x_c^{Discharge} = \sum_{p \in P} \sum_{i \in SU_p} D_{ip} x_{c,ip}^{Source} + \sum_{p \in P} \sum_{r \in R} D_{rp} \, x_{c,rp}^{out} + D_{st} \, x_{c,st}^{out}$$

$$\forall c \in C \tag{65}$$

Moreover, all pollutant discharge concentration must not exceed the maximum specified limits associated with each contaminant.

$$x_c^{Discharge} \leq x_c^{Max} \quad \forall c \in C \tag{66}$$

The optimum pipe diameters were obtained according to recommended velocity ranges (Peters, Timmerhaus et al. 2003). Moreover, the standard diameterswere then obtained by rounding up the calculated values to the nearest standardized values, as specified.

$$DI = Roundup\left(0.363\left(\left(\frac{Flowrate}{3600\rho}\right)^{0.45}\ \rho^{0.13}\right)\right) \tag{67}$$

Alternatively, the roundup function can be replaced by Equations (68) and (69) if a set of discrete pipeline diameters is provided, for which DI∈{DI_1, DI_2, $DI_{3,\ldots,}$ DI_k}, such that:

$$\sum_{k=1}^{n} y_k DI_k \tag{68}$$

$$\sum_{k=1}^{n} y_k = 1 \qquad y_k \in \{0,1\} \tag{69}$$

III.4.2 Pressure Drop Calculations

Since water transport would be associated with some pressure drops being carried in a pipeline, the following calculations for determining pressure drop levels were used (Geankoplis 2008). The velocities in the pipelines were calculated by dividing the stream flowrates with the cross sectional area of the pipe, obtained using the customary diameters of the respective pipe segments

$$v = \frac{4 \times Flowrate}{\pi (DI^c)^2 \rho} \tag{70}$$

Reynolds number was also obtained using the stream customary diameter, velocity, density and viscosity (Geankoplis 2008):

$$N_{Re} = \frac{DI^c v \rho}{\mu} \tag{71}$$

The fanning friction factor was obtained according to Churchill's equation (Geankoplis 2008):

$$f = 8\left[\left(\frac{8}{N_{Re}}\right)^{12} + \left(\frac{1}{A+\left(\frac{37530}{N_{Re}}\right)^{16}}\right)^{1.5}\right]^{\frac{1}{12}} \tag{72}$$

The required parameter A was obtained using the following:

$$A_{st} = \left[-2.457 \ln\left(\left(\frac{7}{N_{Re}}\right)^{0.9} + 0.27\frac{\varepsilon}{DI^c}\right)\right]^{16} \tag{73}$$

The friction losses in the respective pipe segments were then obtained using the fanning friction factor, pipe entrance and exit loss parameters, as well as by obtaining the total numbers of elbows/bends in the pipe and identifying the loss parameters associated with their respective angles.

$$\Delta F^f = \frac{\left(\frac{4fL}{DI^c}+K_{ex}+K_c+K_b\, N^E\right) v^2}{2} \tag{74}$$

Pressure drops were then computed, by multiplying the stream density with the calculated friction loss value.

$$\Delta P^{Drop} = \rho \Delta F^f \tag{75}$$

In addition to computing the pressure drops, total power requirements that are needed to overcome the pressure differences during transportation are then computed (Peters, Timmerhaus et al. 2003) , and were later used to find the total pumping costs.

$$P^W = \frac{g(M)(0.0001P^{Drop})}{3.6\times10^6\, \eta} \tag{76}$$

Equations (71)-(76) were only part of the model that involves pressure drop computations. However, these equations were not part of the optimization problem that involves the determination of viable water allocations.

III.4.3 Implementation

Various solvers that can handle non-convex NLP and MINLPs have been developed (Nannicini & Belotti, 2012). Many of these solvers are primarily based on the branch-and-bound algorithm, which basically involves the identification of lower bounds at each node of the branch-and-bound tree. Such bounds are typically obtained by solving a linear program (LP), based on a relaxation of the corresponding NLP/MINLP problem. Examples of LP-based branch-and-bound solvers for non-convex NLP/MINLPs are Baron, Couenne, and Lindoglobal (Nannicini & Belotti, 2012). In this work, the MINLP optimization problem - given by Equations (1) through (31) - was solved using "what'sBest9.0.5.0" LINDO Global Solver for Microsoft Excel 2010, and run on a desktop PC (Intel® Core ™ i7-2620M, 2.7 GHz, 8.00 GB RAM, 64-bit Operating System).

III.5. Case Study Illustration

In order to demonstrate the application of the methodology within industrial cities based on a given layout and structuring, an industrial city arrangement that has been utilized previously without any treatment considerations (Alnouri, Linke et al. 2014) was used in this work for illustration. Figure 13 shows the industrial city infrastructure with both centralized and decentralized treatment options considered, so as to allow the selection of optimal treatment interception. The total area of the plot is 64 km2, spread over a total of 1600 equally-spaced regions, with each corresponding to an area of 0.04 km2. A total of 6 plants, 6 water sources, and 6 water sinks were used, with similar locations to our previous illustration (Alnouri, Linke et al. 2014a). However, in this case, two different locations for freshwater mains were enabled, with option 1 being a slightly cheaper than option 2, at the expense of providing a lower freshwater quality. Moreover, Figure 13 also illustrates the locations that were retained for water treatment facilities. Plants 2, 3, 4 and 6 all involve on-site treatment options for their respective wastewater discharges.

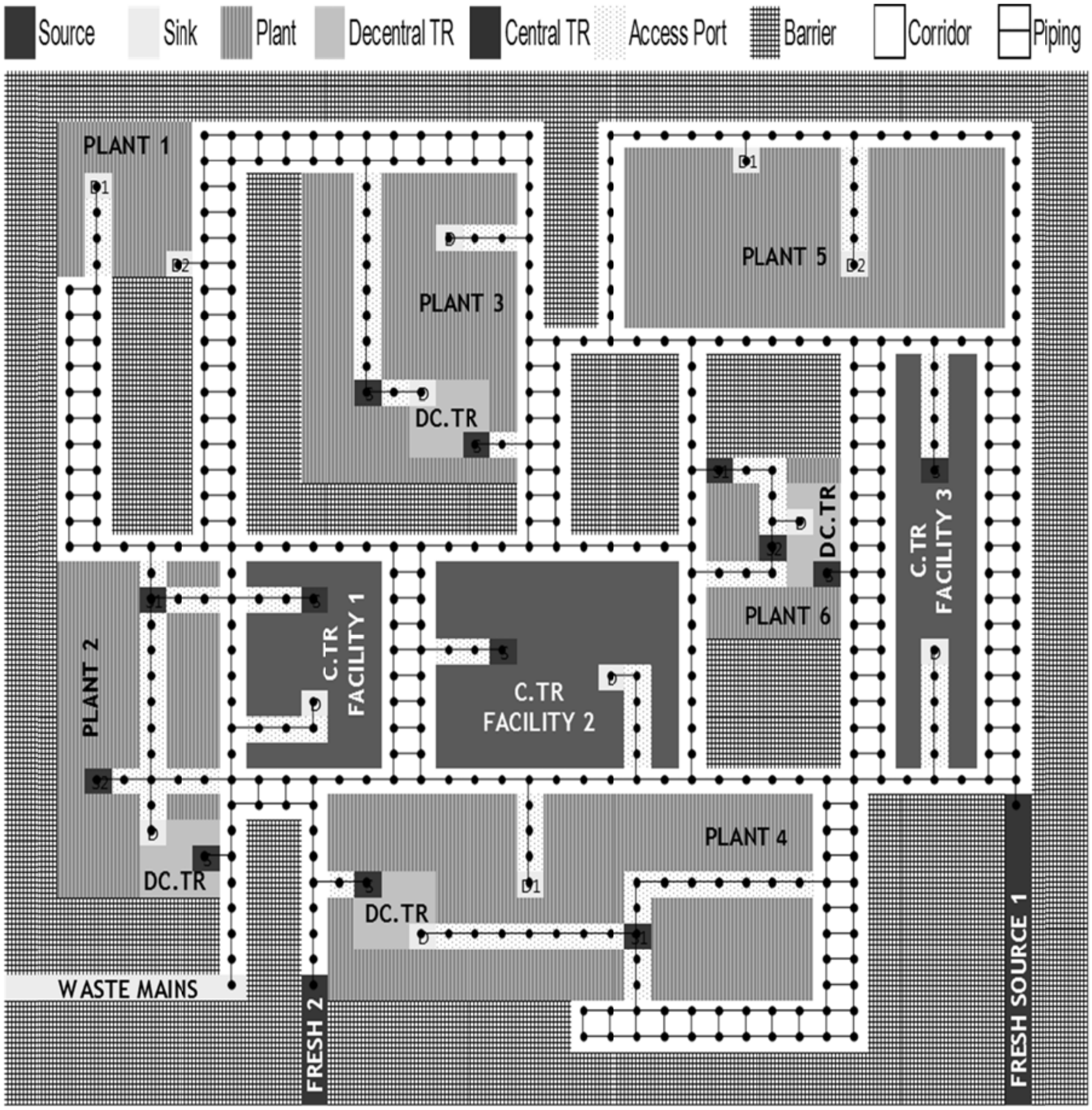

Figure 13. Industrial City Layout, with Type 1 connectivity mesh illustrated

As it has been mentioned before, on-site treatment is restricted to wastewater from within the plant itself, hence no wastewater was allowed to be sent for treatment to a facility located within different plant boundaries. On the other hand, all centralized treatment locations that are indicated on Figure 13 allow wastewater treatment for sources that originate from any of the plants involved. Three different centralized treatment locations are designated, and each of which was allowed to be associated with a selection of treatment technologies (two different options for each) to choose from as desired. Moreover, two different connectivity possibilities were implemented as it has been done previously (Alnouri, Linke et al 2014a). Type 1 and Type 2 connectivity differ in the branching directions that are allowed from node to node, with Type 1 involving right angled turnings only while Type 2 enables diagonal movements from one node to the other. Both types of connectivity meshes are illustrated in Figures 13 and 14 respectively.

Both connectivity settings were utilized as input to a developed Runtest file that allows an automated inputting layout scheme whilst executing Dijkstra's algorithm (Dijkstra 1959). Distance information for all shortest routes that have been attained by executing Dijkstra's algorithm according to the provided layout is summarized in Tables 15-18. Moreover, numbers of elbows and bends within each of shortest routes extracted were also obtained to be utilized in computing pressure drop values, as required. It should be noted that Tables 15 and 16 provide all necessary information based on Type 1 connectivity bounds via available service corridors, while the values in Tables 17 and 18 summarize all necessary information that has been obtained according to Type 2 connectivity mesh boundaries.

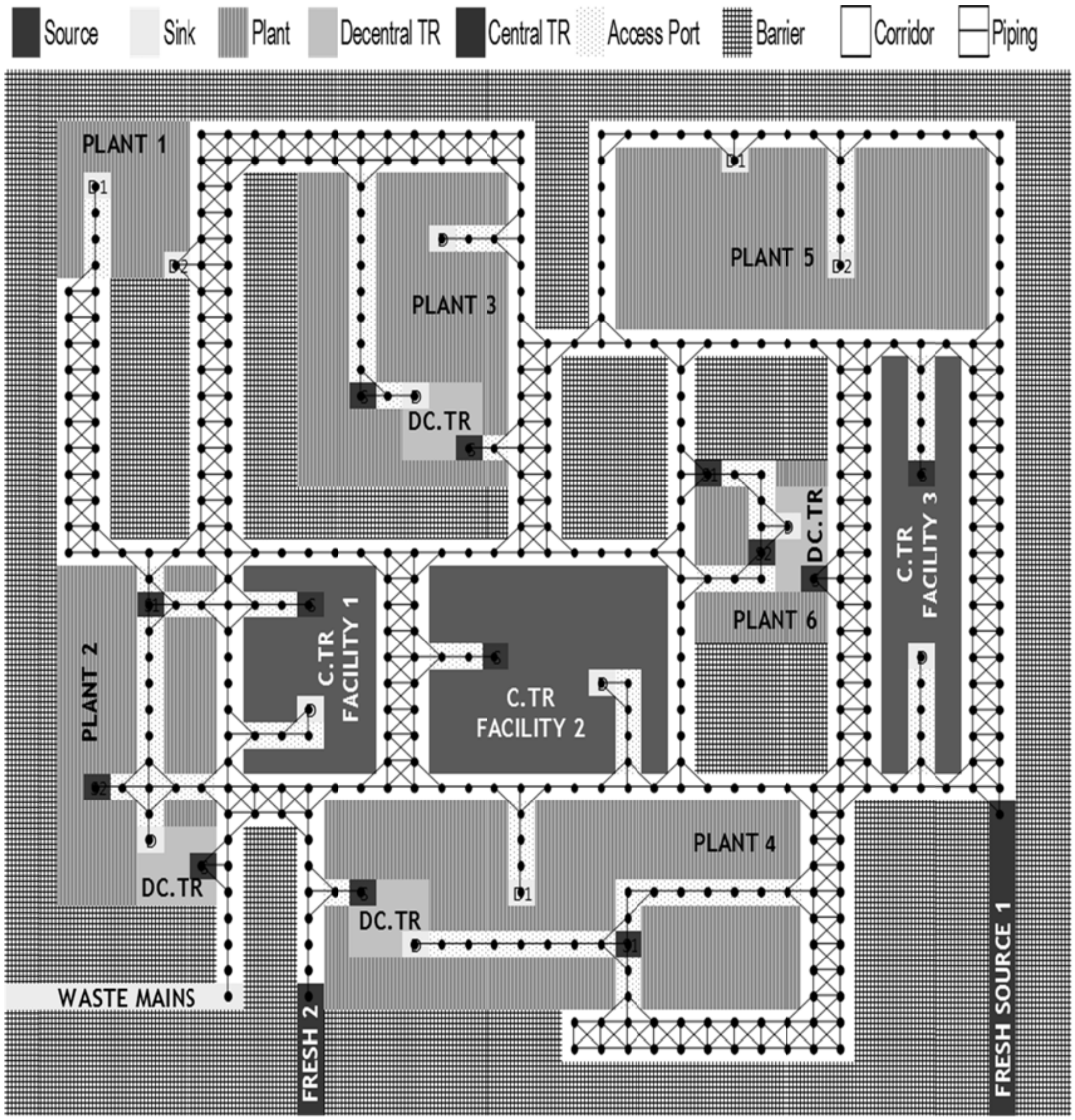

Figure 14. Industrial City Layout, with Type 1 connectivity mesh illustrated

Table 15. Shortest distance data extracted and total number of edges that are associated with right-angled pathways within corridors for water source and sink locations

	Path Distance (km)	P1D1	P1D2	P3D1	P4D1	P5D1	P5D2	Waste
Source-to-Sink; Fresh-to-Sink; Source to-Waste; Fresh –to-Waste	**P2S1**	3.6	3.2	6.2	8.2	9.8	5	3.6
	90^0 Edges	2	3	4	7	7	3	1
	P2S2	5.4	5	8	10	11.6	4	2.6
	90^0 Edges	3	4	4	7	7	1	1
	P3S1	9.6	4	4.2	7.8	9.4	10.2	9.2
	90^0 Edges	4	3	3	6	6	6	2
	P4S1	12.6	11.4	9.6	10.4	11.2	5.6	8.6
	90^0 Edges	6	7	7	8	6	4	6
	P6S1	8	6.8	3.8	4.6	6.2	4.6	7.6
	90^0 Edges	3	4	4	5	5	3	5
	P6S2	8.2	7	4.8	5.6	7.2	4.4	7.4
	90^0 Edges	4	5	5	6	6	4	6
	Fresh 1	11.6	10.4	8.6	7.4	7.4	4.6	38
	90^0 Edges	4	5	5	2	2	2	4
	Fresh 2	7.8	6.6	8	4	10	11.6	17
	90^0 Edges	6	5	5	2	8	8	2

Table 16. Shortest distance data extracted and total number of edges that are associated with right-angled pathways within corridors, for central and de-central water treatment locations

	Path Distance (km)	P2T1	P3T1	P4T1	P6T1	CT1	CT2	CT3
Source-to-Interceptor	**P2S1**	1.8	-	-	-	2.4	6	8.2
	90^0 Edges	0	-	-	-	3	4	3
	P2S2	0.8	-	-	-	2.2	5	7.2
	90^0 Edges	1	-	-	-	3	2	1
	P3S1	-	0.4	-	-	8	10.4	11.8
	90^0 Edges	-	0	-	-	4	7	6
	P4S1	-	-	1.6	-	8.2	5	4.4
	90^0 Edges	-	-	0	-	6	5	4
	P6S1	-	-	-	1	6.4	4	5.4
	90^0 Edges	-	-	-	2	5	4	3
	P6S2	-	-	-	0.4	6.6	3.8	5.2
	90^0 Edges	-	-	-	1	6	5	4

Table16. Continued

	Path Distance (km)	P1D1	P1D2	P3D1	P4D1	P5D1	P5D2	Waste
Interceptor-to-Sink; Interceptor-to-Waste	**P2T1**	6.4	5.2	7.8	3.8	9.8	11.4	1.2
	90^0 Edges	5	4	8	5	11	11	1
	P3T1	7.4	6.2	7.6	3.6	9.6	11.2	3
	90^0 Edges	7	6	6	3	9	9	3
	P4T1	7.2	6	2.6	5.4	4.6	6.2	6.8
	90^0 Edges	3	4	2	5	5	5	7
	P6T1	12	9.2	5.8	5	6.6	7	8
	90^0 Edges	5	6	4	3	5	5	5
	CT1	4.8	3.6	6.2	5	8.2	9.8	3.6
	90^0 Edges	3	4	4	3	7	7	1
	CT2	6.6	5.4	5.2	3.2	7.2	8.8	4.6
	90^0 Edges	3	4	4	3	7	7	5
	CT3	11.6	8.8	5.4	8.2	5.4	5.4	11.2
	90^0 Edges	4	5	3	4	4	4	6

Table 17. Shortest distance data extracted and total number of edges that are associated with diagonally integrated pathways within corridors for water source and sink locations

	Path Distance (km)	P1D1	P1D2	P3D1	P4D1	P5D1	P5D2	Waste
Source-to-Sink; Fresh-to-Sink; Source to-Waste; Fresh –to-Waste	**P2S1**	3.36	2.84	5.72	7.24	8.84	4.64	3.48
	135^0 Edges	2	3	6	9	10	6	2
	P2S2	5.04	4.52	7.28	8.8	10.4	3.88	2.48
	135^0 Edges	4	5	10	13	14	2	2
	P3S1	9	3.52	3.84	7.08	8.68	9.48	8.96
	135^0 Edges	8	5	6	11	12	12	4
	P4S1	11.64	10.32	8.64	9.44	10.24	5.12	8
	135^0 Edges	12	13	16	15	14	8	8
	P6S1	7.64	6.2	3.32	4	5.6	4.24	6.76
	135^0 Edges	5	6	7	8	9	5	9
	P6S2	7.84	6.4	4.2	4.88	6.48	3.92	6.8
	135^0 Edges	5	6	10	11	12	7	7
	Fresh 1	10.88	9.56	7.88	4.36	7.16	7.16	36.2
	135^0 Edges	7	8	11	3	3	4	3
	Fresh 2	6.96	6	7.28	3.76	8.8	10.4	15.8
	135^0 Edges	6	3	10	4	13	14	4

Table 18. Shortest distance data extracted and total number of edges that are associated with diagonally integrated pathways within corridors, for central and de-central water treatment

	Path Distance (km)	**P2T1**	**P3T1**	**P4T1**	**P6T1**	**CT1**	**CT2**	**CT3**
Source-to-Interceptor	**P2S1**	1.8	-	-	-	2.04	5.52	7.84
	135^0 Edges	0	-	-	-	5	7	6
	P2S2	0.68	-	-	-	1.84	4.76	7.08
	135^0 Edges	2	-	-	-	3	3	2
	P3S1	-	0.4	-	-	7.52	9.44	10.96
	135^0 Edges	-	0	-	-	7	11	12
	P4S1	-	-	1.6	-	7.48	4.4	3.8
	135^0 Edges	-	-	0	-	9	9	8
	P6S1	-	-	-	0.76	5.8	3.52	5.04
	135^0 Edges	-	-	-	1	8	4	5
	P6S2	-	-	-	0.28	6	3.2	4.72
	135^0 Edges	-	-	-	0	8	6	7
	Path Distance (km)	**P1D1**	**P1D2**	**P3D1**	**P4D1**	**P5D1**	**P5D2**	**Waste**
Interceptor-to-Sink; Interceptor-to-Waste	**P2T1**	5.8	4.84	6.84	3.32	8.36	9.96	1.08
	135^0 Edges	7	2	11	5	14	1	1
	P3T1	6.44	5.48	6.76	3.24	8.28	9.88	2.64
	135^0 Edges	8	5	12	6	15	6	6
	P4T1	6.84	5.4	2.36	4.8	3.88	5.48	5.96
	135^0 Edges	6	7	4	10	7	10	10
	P6T1	11.16	8.36	5.32	4.64	6	6.28	7.52
	135^0 Edges	9	10	7	5	8	5	5
	CT1	4.44	3.24	5.72	4.64	7.24	8.84	3.48
	135^0 Edges	4	3	6	6	9	2	2
	CT2	6.12	4.68	4.72	2.84	6.24	7.84	4
	135^0 Edges	6	7	8	6	11	6	6
	CT3	11	8.08	5.04	7.6	4.92	4.92	10.12
	135^0 Edges	8	9	6	6	7	12	12

III.5.1 Wastewater Information and Case Study Parameters

In this case study, two different set-ups have been explored for wastewater pollutants: (a) having single contaminant information only and (b) having multiple contaminant information (3 pollutants in this case). For each of these two set-ups, two sets of source wastewater data were considered, lower-end and higher-end contaminant values. A total of four pollutant information scenarios were therefore studied, and each of these cases was explored using both types of connectivity information summarized in Tables 15-18. Tables 19 and 20 show the case study flowrate data, and contaminant composition values that were used for both single and multiple contaminant scenarios, each of which having a lower end and a higher end set of contaminant data for process wastewater sources. Table 21 provides the required flow rates and maximum permissible pollutant limits for each water sink involved. In this case study, the same pollutants were considered to be present in all plants involved. However, different pollutant scenarios can be explored according to the proposed methodology, together with the central and decentral treatment options required for their removal to the appropriate limits.

Table 19. Flow and composition water source data for cases considering a single contaminant only

SOURCES	Flow (W) kg/h	Lower-end Conc. X1 (ppm)	Higher-end Conc. X1 (ppm)
P2S1	80,000	140	400
P2S2	120,000	100	550
P3S1	140,000	180	240
P4S1	100,000	100	1000
P6S1	195,000	250	780
P6S2	80,000	230	810

Table 20. Flow and composition water source data for cases considering multiple contaminants

SOURCES	Flow(W) kg/h	Conc. X1 (ppm)	Conc. X2 (ppm)	Conc. X3 (ppm)	Conc. X1 (ppm)	Conc. X2 (ppm)	Conc. X3 (ppm)
		Lower-end			Higher-end		
P2S1	80,000	140	100	60	400	730	290
P2S2	120,000	100	50	30	550	500	450
P3S1	140,000	180	150	130	240	150	1130
P4S1	100,000	100	190	210	1000	340	670
P6S1	195,000	250	190	200	780	190	500
P6S2	80,000	230	180	180	810	1800	220

Table 21. Flow and composition water sink data

SINKS	Flow (G) kg/h	Max. Inlet Conc. Z1 (ppm)	Max. Inlet Conc. Z1(ppm)	Max. Inlet Conc. Z2 (ppm)	Max. Inlet Conc. Z3 (ppm)
		Single C. Cases	Multiple Contaminant Cases		
P1D1	80,000	50	50	50	80
P1D2	120,000	0	0	0	30
P3D1	80,000	50	50	70	100
P4D1	195,000	240	240	130	150
P5D1	140,000	140	140	100	100
P5D2	80,000	170	170	120	130

Table 22 summarizes all the parameters associated with the different water treatment interceptor options in terms of pollutant removal ratios, as well as costing. Fixed unit costs for all on-site (decentralized) water treatment were considered to be zero, since it was assumed that they already exist as part of the plant's infrastructure, and hence no investment costs were expected to be involved, and only operating costs were incorporated. On the other hand, all off-site (centralized) treatment interceptor selections were assumed to incorporate both a fixed investment parameter, as well as an operational cost per the amount of pollutant removed. Moreover, two different treatment choices were associated with each of the off-site treatment locations, and the information for which is also summarized in Table 22. The model also takes into consideration the costs of the different treatment options that are put forth, when selecting the different treatment technologies to be used in the network. Moreover, in this study, the calculated pipeline diameters were rounded up to the nearest standard size in meters, in increments of 0.1. However, any set of standard sizes can be incorporated, depending on what the user would like to specify.

Table 22. Contaminant removal ratios and cost of respective treatment scenario

Treatment Interceptor	X1 Removal Ratio	X2 Removal Ratio	X3 Removal Ratio	Unit cost of Interceptor CU ($)	Unit Cost of mass removed CUM ($-kg removed)
P2T1	0.9	0.5	0.5	0	1.06
P3T1	0.6	0.8	0.6	0	1.53
P4T1	0.7	0.7	0.7	0	1.78
P6T1	0.8	0.7	0.7	0	1.82
CT1 Option 1	0.7	0.8	0.9	2,400	1.54
CT1 Option 2	0.7	0.9	0.9	3,700	0.695
CT2 Option 1	0.9	0.8	0.7	9,200	0.85
CT2 Option 2	0.8	0.8	0.9	8,800	1.005
CT3 Option 1	0.9	0.9	0.9	10,200	1.102
CT3 Option 2	0.95	0.95	0.95	11,600	1.34

Moreover, cost parameters (a and b) depend on the material of construction utilized, which was assumed to be carbon steel in this study. Therefore, different pipeline materials would definitely require utilizing the corresponding values for these parameters, based on the material specified. Table 23 outlines all the additional parameters that were required in this case study, and most of the values were adopted form a study by Rubio-Castro et al. (2011). The costs of fresh water, wastewater discharge, treatment units, and interplant pipelines were accounted for. Moreover, environmental regulations for streams discharged to the environment were also incorporated.

Table 23. Case Study Parameters

Parameter	Value
Pipe Roughness $\boldsymbol{\varepsilon}$	4.6 x10^{-5}
Expansion loss at pipe exit $\boldsymbol{K_{ex}}$	0.55
Contraction loss at pipe entrance $\boldsymbol{K_c}$	0.55
Loss at pipe elbow/bend $\boldsymbol{K_b}$	0.75
Loss at pipe elbow/bend $\boldsymbol{K_b}$	0.5
Density ρ	1000 (kg/m^3)
Viscosity μ	0.00155 (kg/m s)
Coefficient associated with piping cost calculations a	1.215
Coefficient associated with piping cost calculations *b*	2.843
Cost of Wastewater Discharge $\boldsymbol{C^{WASTE}}$	0.3 $/ton
Cost of Freshwater of type 1 $\boldsymbol{C_l^{FRESH}}$	0.1 $/ton
Cost of Freshwater of type 2 $\boldsymbol{C_l^{FRESH}}$	0.13 $/ton
Pollutant 1-3 compositions in External Freshwater of type *1* $\boldsymbol{x_{c,1}^{FRESH}}$	10 ppm; 10 ppm; 10 ppm
Pollutant 1-3 compositions in External Freshwater of type *2* $\boldsymbol{x_{c,2}^{FRESH}}$	5 ppm; 5 ppm; 5 ppm
Maximum permissible discharge concentration of pollutants 1-3 for Lower-End Case$\boldsymbol{x_c^{Max}}$	120 ppm; 100 ppm; 90 ppm

Table 23. Continued

Parameter	**Value**
Maximum permissible discharge concentration of pollutants 1-3 for Higher-End Case x_c^{Max}	120 ppm; 150 ppm; 200ppm
Operating hours per year H_y	8760 h/yr
Treatment Annualized Factor K_F	0.05 yr^{-1}
Piping Cost Annualized Factor γ	0.05 yr^{-1}
Efficiency η	80%

III.5.2 Case Study Results

All the cases that have been considered were optimized based on three different settings: (1) allowing on-site 'decentral' treatment only (2) allowing off-site 'central' treatment only and (3) allowing both on-site and off-site treatment simultaneously. Table 24 provides a summary of descriptions for the 24 cases studied. All cases have been solved by means of global optimization for non-convex problems, via branch-and bound algorithm. The number of equations, continuous, and binary variables involved in each of the 3 settings described were as follows: (1) 17,778 numerics, 769 variables, 532 constraints, 0 binaries and 1510 coefficients; (2) 17483 numerics, 997 variables, 532 constraints, 6 binaries and 2270 coefficients; (3) 17,427 numerics, 1,118 variables, 532 constraints, 6 binaries and 2784 coefficients. The number of iterations varied between 10,000-2,000,000 depending on the cases described, with a solver feasibility tolerance of 0.00001. The current implementation of the model in LINDO WHAT'SBEST has been able to converge using the roundup function for determining pipeline diameters.

Table 24. Case Descriptions

Case	Description
1	Single Contaminant; lower-end concentrations for wastewater sources; Type 1 connectivity; onsite treatment enabled only
2	Single Contaminant; lower-end concentrations for wastewater sources; Type 1 connectivity; offsite treatment enabled only
3	Single Contaminant; lower-end concentrations for wastewater sources; Type 1 connectivity; both onsite and offsite treatment enabled simultaneously
4	Single Contaminant; lower-end concentrations for wastewater sources; Type 2 connectivity; onsite treatment enabled only
5	Single Contaminant; lower-end concentrations for wastewater sources; Type 2 connectivity; offsite treatment enabled only
6	Single Contaminant; lower-end concentrations for wastewater sources; Type 2 connectivity; both onsite and offsite treatment enabled simultaneously
7	Multiple Contaminants; lower-end concentrations for wastewater sources; Type 1 connectivity; onsite treatment enabled only
8	Multiple Contaminants; lower-end concentrations for wastewater sources; Type 1 connectivity; offsite treatment enabled only
9	Multiple Contaminants; lower-end concentrations for wastewater sources; Type 1 connectivity; both onsite and offsite treatment enabled simultaneously
10	Multiple Contaminants; lower-end concentrations for wastewater sources; Type 2 connectivity; onsite treatment enabled only
11	Multiple Contaminants; lower-end concentrations for wastewater sources; Type 2 connectivity; offsite treatment enabled only
12	Multiple Contaminants; lower-end concentrations for wastewater sources; Type 2 connectivity; both onsite and offsite treatment enabled simultaneously

Table 24. Continued

Case	Description
13	Single Contaminant; higher-end concentrations for wastewater sources; Type 1 connectivity; onsite treatment enabled only
14	Single Contaminant; higher-end concentrations for wastewater sources; Type 1 connectivity; offsite treatment enabled only
15	Single Contaminant; higher-end concentrations for wastewater sources; Type 1 connectivity; both onsite and offsite treatment enabled simultaneously
16	Single Contaminant; higher-end concentrations for wastewater sources; Type 2 connectivity; onsite treatment enabled only
17	Single Contaminant; higher-end concentrations for wastewater sources; Type 2 connectivity; offsite treatment enabled only
18	Single Contaminant; higher-end concentrations for wastewater sources; Type 2 connectivity; both onsite and offsite treatment enabled simultaneously
19	Multiple Contaminants; higher-end concentrations for wastewater sources; Type 1 connectivity; onsite treatment enabled only
20	Multiple Contaminants; higher-end concentrations for wastewater sources; Type 1 connectivity; offsite treatment enabled only
21	Multiple Contaminants; higher-end concentrations for wastewater sources; Type 1 connectivity; both onsite and offsite treatment enabled simultaneously
22	Multiple Contaminants; higher-end concentrations for wastewater sources; Type 2 connectivity; onsite treatment enabled only
23	Multiple Contaminants; higher-end concentrations for wastewater sources; Type 2 connectivity; offsite treatment enabled only
24	Multiple Contaminants; higher-end concentrations for wastewater sources; Type 2 connectivity; both onsite and offsite treatment enabled simultaneously

The various water network solutions were obtained in relatively reasonable CPU timings, for all the different scenarios that have been studied. All cases converged in less than 7 minutes of CPU time. The results obtained indicate various interesting trends, and Tables 25-31 outline the various source-interception-sink implementations that have been found. Similar implementations were obtained for more than one case, and each of the solutions greatly depends on the conditions involved and type of treatment enabled. All cases in which both on-site and off-site treatment options were allowed simultaneously yield the best performing results, with the least freshwater consumption and wastewater discharge.

Table 25. Optimum Source-Interception-Sink mapping implementation obtained for Cases 1, 3, 4 and 6

		Flows (ton/h)						
		P1D1	**P1D2**	**P3D1**	**P4D1**	**P5D1**	**P5D2**	**Waste**
Source-to-Sink; Fresh-to-Sink; Source to-Waste; Fresh –to-Waste	**P2S1**	0	0	0	0	0	0	0
	P2S2	0	0	0	0	0	1.44	0
	P3S1	0	0	6.38	8.39	50.75	74.49	0
	P4S1	0	0	22.59	0	77.41	0	0
	P6S1	12.88	0	0	118.5	0	0	63.65
	P6S2	0	0	0	68.15	11.85	0	0
	Fresh 1	0	0	0	0	0	0	0
	Fresh 2	0	120.0	0	0	0	0	0
		P2T1	**P3T1**	**P4T1**	**P6T1**	**CT1**	**CT2**	**CT3**
Source-to-interceptor	**P2S1**	80.0	0	0	0	0	0	0
	P2S2	118.5	0	0	0	0	0	0
	P3S1	0	0	0	0	0	0	0
	P4S1	0	0	0	0	0	0	0
	P6S1	0	0	0	0	0	0	0
	P6S2	0	0	0	0	0	0	0
		P1D1	**P1D2**	**P3D1**	**P4D1**	**P5D1**	**P5D2**	**Waste**
Interceptor -to-Sink; Interceptor -to-Waste	**P2T1**	67.17	0	51.02	0	0	4.06	76.3
	P3T1	0	0	0	0	0	0	0
	P4T1	0	0	0	0	0	0	0
	P6T1	0	0	0	0	0	0	0

Table 26. Optimum Source-Interception-Sink mapping implementation obtained for Cases 2, 5

		Flows (ton/h)						
		P1D1	**P1D2**	**P3D1**	**P4D1**	**P5D1**	**P5D2**	**Waste**
Source-to-Sink; Fresh-to-Sink; Source to-Waste; Fresh –to-Waste	**P2S1**	0	0	0	0	10.19	0	69.81
	P2S2	0	0	0	0	0	0	120.0
	P3S1	19.19	0	19.19	22.33	47.46	31.83	0
	P4S1	0	0	0	0	0	0	100.0
	P6S1	0	0	0	153.3	10.42	8.15	23.11
	P6S2	2.37	0	2.37	19.36	30.54	25.35	0
	Fresh 1	0	0	0	0	0	0	0
	Fresh 2	58.44	120.0	58.44	0	41.38	14.66	0
		P2T1	**P3T1**	**P4T1**	**P6T1**	**CT1**	**CT2**	**CT3**
Source-to-interceptor	**P2S1**	-	-	-	-	0	0	0
	P2S2	-	-	-	-	0	0	0
	P3S1	-	-	-	-	0	0	0
	P4S1	-	-	-	-	0	0	0
	P6S1	-	-	-	-	0	0	0
	P6S2	-	-	-	-	0	0	0
		P1D1	**P1D2**	**P3D1**	**P4D1**	**P5D1**	**P5D2**	**Waste**
Interceptor-to-Sink; Interceptor-to-Waste	**CT1**	0	0	0	0	0	0	0
	CT2	0	0	0	0	0	0	0
	CT3	0	0	0	0	0	0	0

Table 27. Optimum Source-Interception-Sink mapping implementation obtained for Cases 7, 10

		Flows (ton/h)						
		P1D1	**P1D2**	**P3D1**	**P4D1**	**P5D1**	**P5D2**	**Waste**
Source-to-Sink; Fresh-to-Sink; Source to-Waste; Fresh –to-Waste	**P2S1**	0	0	0	0	15.39	0	51.99
	P2S2	0	0	0	0	0	0	120.0
	P3S1	0	0	0	0	0	0	0
	P4S1	21.05	0	26.52	1.77	0	0	50.66
	P6S1	0	0	0	120.1	61.55	13.34	0
	P6S2	0	0	0	68.15	11.85	0	41.54
	Fresh 1	0	0	0	0	0	0	0
	Fresh 2	58.95	120.0	34.78	0	58.8	2.16	0
		P2T1	**P3T1**	**P4T1**	**P6T1**	**CT1**	**CT2**	**CT3**
Source-to-interceptor	**P2S1**	12.62	0	0	0	-	-	-
	P2S2	0	0	0	0	-	-	-
	P3S1	0	140.0	0	0	-	-	-
	P4S1	0	0	0	0	-	-	-
	P6S1	0	0	0	0	-	-	-
	P6S2	0	0	0	0	-	-	-

Table 27. Continued

		P1D1	P1D2	P3D1	P4D1	P5D1	P5D2	Waste
Interceptor-to-Sink; Interceptor-to-Waste	**P2T1**	0	0	0	0	0	0	12.62
	P3T1	0	0	18.69	73.12	0	30.3	17.88
	P4T1	0	0	0	0	0	0	0
	P6T1	0	0	0	0	0	0	0

Table 28. Optimum Source-Interception-Sink mapping implementation obtained for Cases 8,9, 11 and 12

		Flows (ton/h)						
		P1D1	**P1D2**	**P3D1**	**P4D1**	**P5D1**	**P5D2**	**Waste**
Source-to-Sink; Fresh-to-Sink; Source to-Waste; Fresh –to-Waste	**P2S1**	0	0	0	0	0	37.38	42.62
	P2S2	0	0	0	60.29	53.52	6.19	0
	P3S1	0	0	0	0	0	0	24.13
	P4S1	0	0	10.38	0	0	0	0
	P6S1	8.26	0	0	105.3	53.77	27.66	0
	P6S2	0	0	8.68	9.11	0	0	24.88
	Fresh 1	0	0	0	0	0	0	0
	Fresh 2	0	120	0	0	0	0	0
		P2T1	**P3T1**	**P4T1**	**P6T1**	**CT1**	**CT2** Opn.1	**CT3**
Source-to-interceptor	**P2S1**	0	0	0	0	0	0	0
	P2S2	0	0	0	0	0	0	0
	P3S1	0	0	0	0	0	115.8	0
	P4S1	0	0	0	0	0	89.6	0
	P6S1	0	0	0	0	0	0	0
	P6S2	0	0	0	0	0	37.32	0
		P1D1	**P1D2**	**P3D1**	**P4D1**	**P5D1**	**P5D2**	**Waste**
Interceptor-to-Sink; Interceptor-to-Waste	**CT1**	0	0	0	0	0	0	0
	CT2 Opn.1	71.73	0	60.93	20.29	32.71	8.77	48.35
	CT3	0	0	0	0	0	0	0

Table 29. Optimum Source-Interception-Sink mapping implementation obtained for Cases 14 and 17

		Flows (ton/h)						
		P1D1	**P1D2**	**P3D1**	**P4D1**	**P5D1**	**P5D2**	**Waste**
Source-to-Sink; Fresh-to-Sink; Source to-Waste; Fresh –to-Waste	**P2S1**	0	0	0	0	0	0	0
	P2S2	0	0	0	0	0	0	0
	P3S1	0	0	0	0	0	0	0
	P4S1	0	0	0	37.55	12.09	9.46	10.66
	P6S1	0	0	0	0	0	0	0
	P6S2	0	0	0	0	0	0	0
	Fresh 1	0	0	0	0	0	0	0
	Fresh 2	11.85	120.0	11.85	0	0	0	0
		P2T1	**P3T1**	**P4T1**	**P6T1**	**CT1**	**CT2** Opn. 1	**CT3**
Source-to-interceptor	**P2S1**	-	-	-	-	0	80.0	0
	P2S2	-	-	-	-	0	120.0	0
	P3S1	-	-	-	-	0	140.0	0
	P4S1	-	-	-	-	0	30.22	0
	P6S1	-	-	-	-	0	195	0
	P6S2	-	-	-	-	0	80	0
		P1D1	**P1D2**	**P3D1**	**P4D1**	**P5D1**	**P5D2**	**Waste**
Interceptor-to-Sink; Interceptor-to-Waste	**CT1**	0	0	0	0	0	0	0
	CT2 Opn. 1	68.15	0	68.15	157.4	127.91	70.54	153.0
	CT3	0	0	0	0	0	0	0

Table 30. Optimum Source-Interception-Sink mapping implementation obtained for Cases 15 and 18

		Flows (ton/h)						
		P1D1	**P1D2**	**P3D1**	**P4D1**	**P5D1**	**P5D2**	**Waste**
Source-to-Sink; Fresh-to-Sink; Source to-Waste; Fresh –to-Waste	**P2S1**	0	0	0	0	0	0	0
	P2S2	0	0	0	22.17	16.66	14.68	0
	P3S1	0	0	0	128.6	0	0	11.39
	P4S1	0	0	0	0	0	0	0
	P6S1	0	0	0	0	0	0	4.58
	P6S2	0	0	0	0	0	0	0
	Fresh 1	0	0	0	0	0	0	0
	Fresh 2	0	120.0	0	0	0	0	0

Table 30. Continued

		P2T1	P3T1	P4T1	P6T1	CT1	CT2 Opn.1	CT3
	P2S1	80.0	0	0	0	0	0	0
	P2S2	66.48	0	0	0	0	0	0
Source-to-interceptor	**P3S1**	0	0	0	0	0	0	0
	P4S1	0	0	0	0	0	100	0
	P6S1	0	0	0	0	0	190.4	0
	P6S2	0	0	0	0	0	80.0	0
		P1D1	**P1D2**	**P3D1**	**P4D1**	**P5D1**	**P5D2**	**Waste**
	P2T1	73.24	0	73.24	0	0	0	0
	P3T1	0	0	0	0	0	0	0
Interceptor-to-Sink; Interceptor-to-Waste	**P4T1**	0	0	0	0	0	0	0
	P6T1	0	0	0	0	0	0	0
	CT1	0	0	0	0	0	0	0
	CT2 Opn.1	6.75	0	6.75	44.22	123.33	65.31	124.0
	CT3	0	0	0	0	0	0	0

Table 31. Optimum Source-Interception-Sink mapping implementation obtained for Cases 20,21, 23 and 24

		Flows (ton/h)						
		P1D1	**P1D2**	**P3D1**	**P4D1**	**P5D1**	**P5D2**	**Waste**
Source-to-Sink;	**P2S1**	0	0	0	0	0	0	3.86
	P2S2	0	0	0	0	0	0	0
Fresh-to-Sink;	**P3S1**	0	0	0	0	0	0	0
	P4S1	0	0	0	0	0	0	0
Source to-Waste;	**P6S1**	2.20	0	0.99	49.70	17.96	12.61	27.72
	P6S2	0.29	0	0.70	7.47	4.29	2.76	12.42
Fresh –to-Waste	**Fresh 1**	51.59	0	40.0	125.5	98.53	46.62	0
	Fresh 2	0	120	0	0	0	0	0

Table 31. Continued

		P2T1	P3T1	P4T1	P6T1	CT1	CT2 Op1	CT3
Source-to-interceptor	P2S1	0	0	0	0	0	76.14	0
	P2S2	0	0	0	0	0	120	0
	P3S1	0	0	0	0	0	140	0
	P4S1	0	0	0	0	0	100	0
	P6S1	0	0	0	0	0	83.82	0
	P6S2	0	0	0	0	0	52.06	0
		P1D1	**P1D2**	**P3D1**	**P4D1**	**P5D1**	**P5D2**	**Waste**
Interceptor-to-Sink; Interceptor-to-Waste	CT1	0	0	0	0	0	0	0
	CT2 Opn.1	25.91	0	38.31	12.26	19.21	18.00	458.1
	CT3	0	0	0	0	0	0	0

Tables 32 and 33 summarize all costs of the solutions attained for the different cases, using lower end and higher end contaminant information respectively. The costing included piping, freshwater intake, wastewater discharge, water treatment, and pumping costs required to overcome pressure drops. The lowest freshwater consumption and wastewater discharge flowrate values were 120 t/h and 140 t/h respectively, whereas the highest were 482.2 t/h and 502.3 t/h. Moreover, the results show that piping and pumping costs are important factors that must be considered in the design stage, since the costs constitute a significant portion of the total costs, and can significantly vary depending on the water allocations achieved (38-53% for cases1-6; 31-43% for cases 7-12; 21-23% for cases 13-18; and 20-21% for cases 19-24).

Additionally, all cases have been re-solved by utilizing a continuous value for all pipeline diameters, so as to compare the effect of retaining a continuous diameter value, on the solutions attained.. It has been found that the water allocations obtained were not influenced by replacing the roundup diameter function with a continuous diameter value. However, all piping and pumping costs were affected. The corresponding results for all resolved cases have been summarized in Tables 32-33. Even though pipeline costs decrease when a continuous diameter variable is utilized, pumping costs increase due to larger pressure drop differences obtained, as a result of increased friction losses. However, since pipeline costs outweigh pumping costs, the total annualized costs decrease in all cases.

Table 25 summarizes the solution attained using the lower-end single contaminant information, whilst enabling on-site treatment only (Cases 1 and 4). When both central and decentral treatment options were allowed simultaneously (Cases 3 and 6), a similar implementation was attained. Additionally, it can be noted that the second freshwater option was mostly chosen due to the more accessible location and cleaner source, despite it being slightly more expensive in terms of cost per ton of supply. Table 26 outlines the optimum cost implementation obtained for Cases 2 and 5, in which only off-site central treatment was enabled. It was observed that no central treatment options were chosen, even after allowing the option. When comparing Cases 1-6, it can be noted that on-site decentral treatment was found to give the most economical results. For the cases that only allowed off-site central treatment, water integration was mainly achieved via direct recycling of existing process wastewater sources. Table 27 provides the optimum cost source-interception-sink mapping implementation obtained using the lower-end multiple contaminant compositions, whilst only allowing on-site decentral treatment options (Cases 7 and 10). It can be observed that ultimately, more freshwater was required than when a single contaminant was involved. The optimum cost implementation for Cases 8,9, 11 and 12 is outlined in Table 28, and was found to be similar for the case employing of off-site treatment only (Cases 8 and 11) as well as allowing both on-site and off-site treatment (Cases 9 and 12). When comparing Cases 7-12, in which lower end multiple pollutant information was involved, it was observed that off-site central treatment was found to give the most economical results, unlike the cases that employed lower end single contaminant data. Moreover, the solutions were found to incorporate location 2 for off-site centralized water treatment, with option 1 selected. Figures 15-19 provide some example illustrations for the water network connectivity that have been obtained, according to the solutions outlined.

Table 32. Summary of costs using lower end concentration data

	Right Angled Pathways			Diagonally Integrated Pathways		
	Decentral Treat. Only	**Central Treat. Only**	**Both Enabled**	**Decentral Treat. Only**	**Central Treat. Only**	**Both Enabled**
	Single Contaminant Considered					
Annualized Piping Costs (PC) $/yr	566,477	580,621	566,477	516,520	527,320	516,520
External Freshwater Costs (FC) $/yr	136,656	333,573	136,656	136,656	333,573	136,656
Annual Water Treatment Costs (TC) $/yr	192,676	0	192,676	192,676	0	192,676
Wastewater Discharge Costs (WC) $/yr	367,920	822,345	367,920	367,920	822,345	367,920
Total PC+FC+TC+WC ($/yr)	1,263,729	1,736,540	1,263,729	1,213,773	1,683,238	1,213,773
Freshwater Required (kg/h)	120,000	292,916	120,000	120,000	292,916	120,000
Wastewater Discharged (kg/h)	140,000	312,916	140,000	140,000	312,916	140,000
Pumping Costs Required $/yr	114,325	128,487	114,325	103,636	117,719	103,636
Total PC+FC+TC+WC ($/yr)*	1,081,935	1,536,662	1,081,935	1,047,829	1,501,763	1,047,829
Annualized Piping Costs (PC) $/yr*	384,683	380,743	384,683	350,577	345,845	350,577
Pumping Costs Required $/yr*	314,991	364,101	314,991	286,304	331,934	286,304

* Results when all diameter variables were kept as continuous variables, and no rounding functions were utilized in the calculations

Table 32. Continued

	Right Angled Pathways			Diagonally Integrated Pathways		
	Decentral Treat. Only	**Central Treat. Only**	**Both Enabled**	**Decentral Treat. Only**	**Central Treat. Only**	**Both Enabled**
	Multiple Contaminants Considered					
Annualized Piping Costs (PC) $/yr	666,807	722,768	722,768	604,157	655,489	655,489
External Freshwater Costs (FC) $/yr	312,816	136,656	136,656	312,816	136,656	136,656
Annual Water Treatment Costs (TC) $/yr	594,802	813,258	813,258	594,802	813,258	813,258
Wastewater Discharge Costs (WC) $/yr	774,443	367,920	367,920	774,443	367,920	367,920
Total PC+FC+TC+WC ($/yr)	2,348,869	2,040,602	2,040,602	2,286,219	1,973,323	1,973,323
Freshwater Required (kg/h)	274,689	120,000	120,000	274,689	120,000	120,000
Wastewater Discharged (kg/h)	294,689	140,000	140,000	294,689	140,000	140,000
Pumping Costs Required $/yr	125,529	154,595	154,595	114,097	140,959	140,959
Total PC+FC+TC+WC ($/yr)*	2,102,594	1,811,652	1,811,652	2,063,385	1,766,395	1,766,395
Annualized Piping Costs (PC) $/yr*	420,531	493,818	493,818	381,323	448,561	448,561
Pumping Costs Required $/yr*	353,410	387,862	387,862	320,877	351,235	351,235

* Results when all diameter variables were kept as continuous variables, and no rounding functions were utilized in the calculations

Table 33. Summary of costs using higher end concentration data

	Right Angled Pathways			Diagonally Integrated Pathways		
	Decentral Treat. Only	**Central Treat. Only**	**Both Enabled**	**Decentral Treat. Only**	**Central Treat. Only**	**Both Enabled**
	Single Contaminant Considered					
Annualized Piping Costs (PC) $/yr	-	787,624	692,128	-	778,568	680,945
External Freshwater Costs (FC) $/yr	-	163,652	136,656	-	163,652	136,656
Annual Water Treatment Costs (TC) $/yr	-	2,734,887	2,806,208	-	2,734,887	2,806,208
Wastewater Discharge Costs (WC) $/yr	-	430,220	367,920	-	430,220	367,920
Total PC+FC+TC+ WC ($/yr)	-	4,116,384	4,002,912	-	4,107,328	3,991,729
Freshwater Required (kg/h)	-	143,706	120,000	-	143,706	120,000
Wastewater Discharged (kg/h)	-	163,706	140,000	-	163,706	140,000
Pumping Costs Required $/yr	-	151,646	188,809	-	151,090	183,491
Total PC+FC+TC+ WC ($/yr)*	-	3,886,953	3,822,236	-	3,881,951	3,813,390
Annualized Piping Costs (PC) $/yr*	-	558,193	511,451	-	553,191	502,606
Pumping Costs Required $/yr*	-	407,276	353,933	-	402,760	345,758

* Results when all diameter variables were kept as continuous variables, and no rounding functions were utilized in the calculations

Table 33. Continued

	Right Angled Pathways			Diagonally Integrated Pathways		
	Decentral Treat. Only	**Central Treat. Only**	**Both Enabled**	**Decentral Treat. Only**	**Central Treat. Only**	**Both Enabled**
			Multiple Contaminants Considered			
Annualized Piping Costs (PC) $/yr	-	827,226	827,226	-	800,140	800,140
External Freshwater Costs (FC) $/yr	-	454,061	454,061	-	454,061	454,061
Annual Water Treatment Costs (TC) $/yr	-	5,933,909	5,933,909	-	5,933,909	5,933,909
Wastewater Discharge Costs (WC) $/yr	-	1,320,137	1,320,137	-	1,320,137	1,320,137
Total PC+FC+TC+WC ($/yr)	-	8,535,334	8,535,334	-	8,508,248	8,508,248
Freshwater Required (kg/h)	-	482,335	482,335	-	482,335	482,335
Wastewater Discharged (kg/h)	-	502,335	502,335	-	502,335	502,335
Pumping Costs Required $/yr	-	934,172	934,172	-	905,463	905,463
Total PC+FC+TC+WC ($/yr)*	-	8,273,850	8,273,850	-	8,258,828	8,258,828
Annualized Piping Costs (PC) $/yr*	-	565,743	565,743	-	550,720	550,720
Pumping Costs Required $/yr*	-	1,799,326	1,799,326	-	1,728,502	1,728,502

* Results when all diameter variables were kept as continuous variables, and no rounding functions were utilized in the calculations

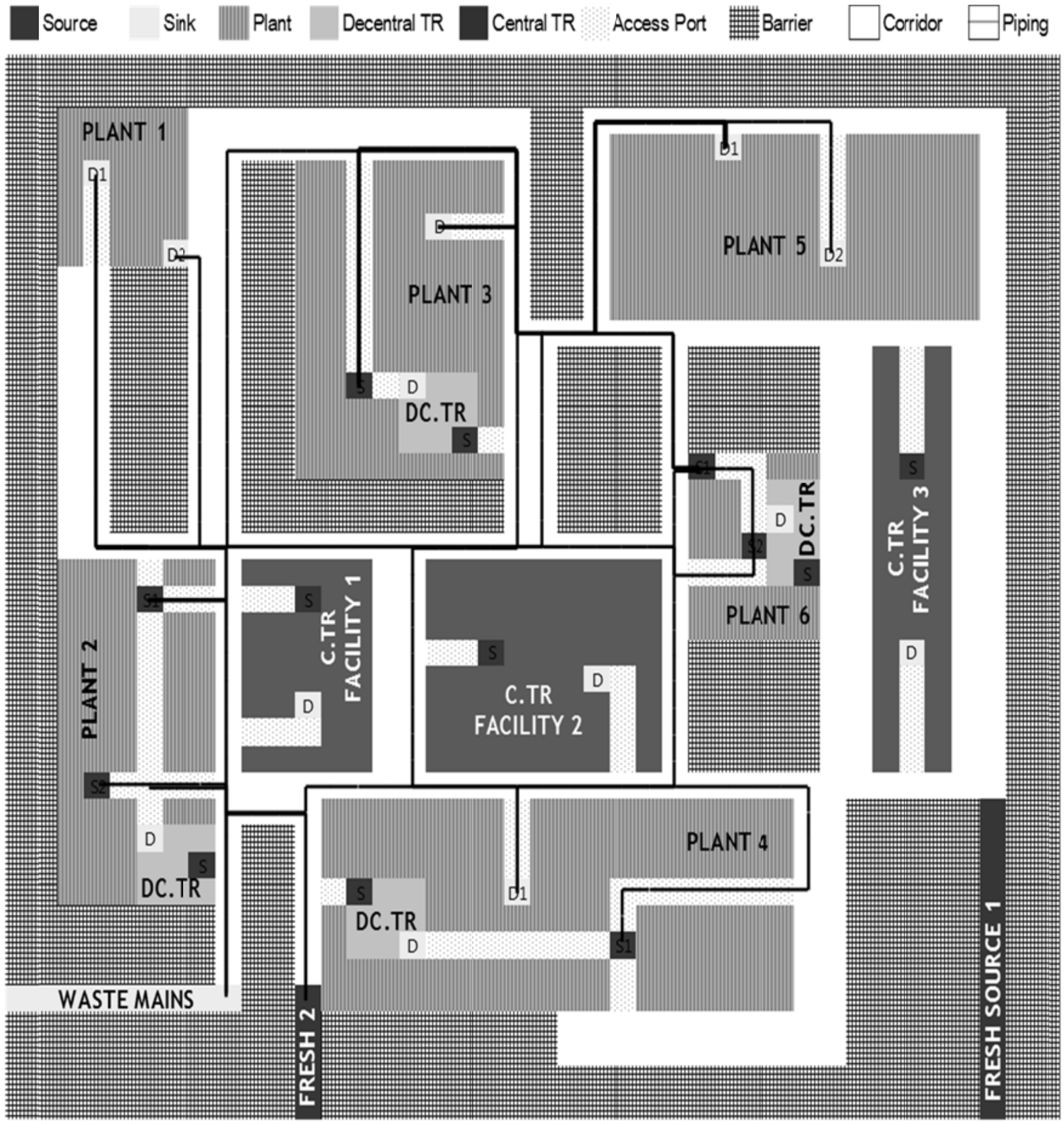

Figure 15. Example Solution Illustrated for Case 2

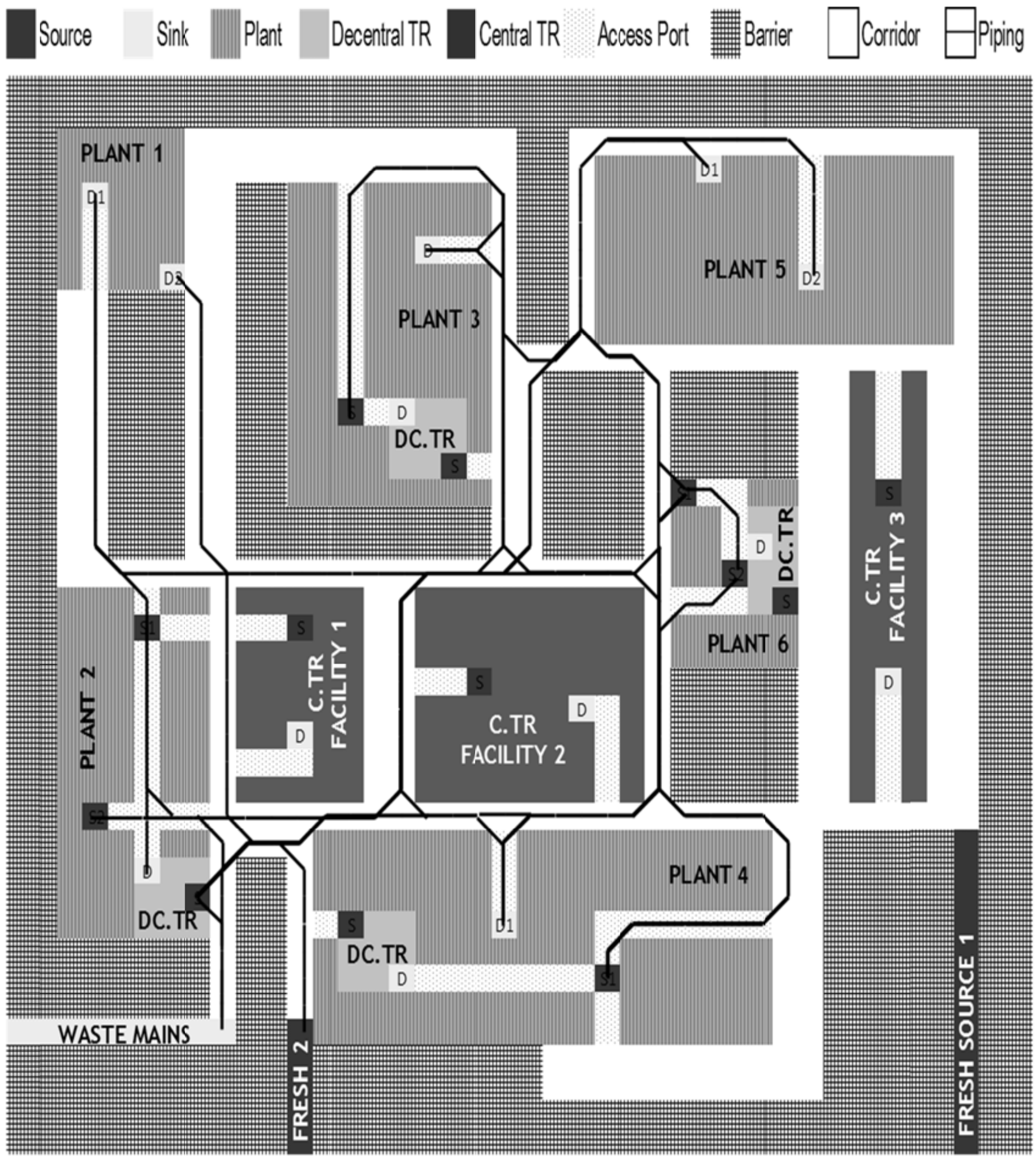

Figure 16. Example Solution Illustrated for Cases 4 and 6

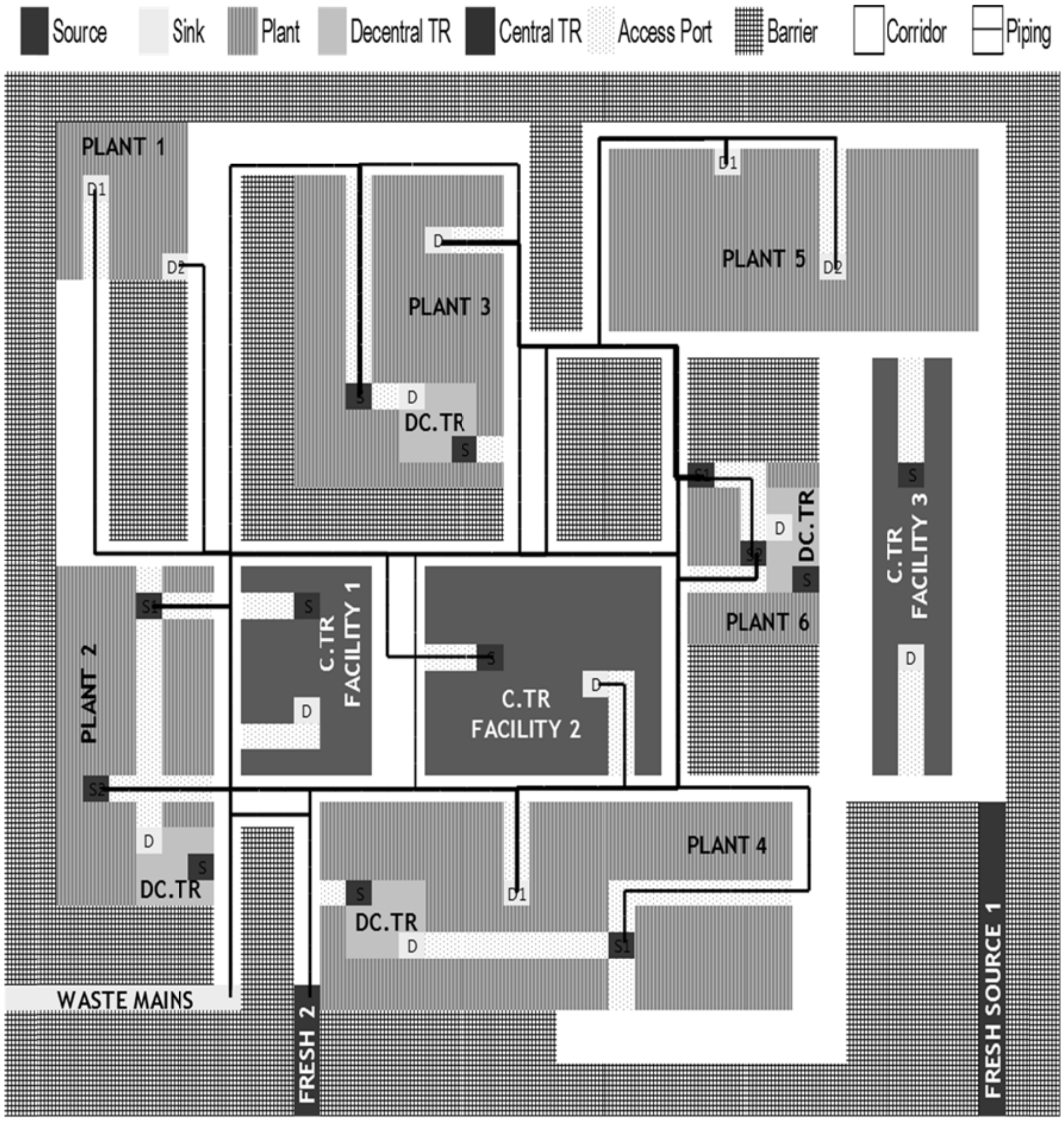

Figure 17. Example Solution Illustrated for Cases 8 and 9

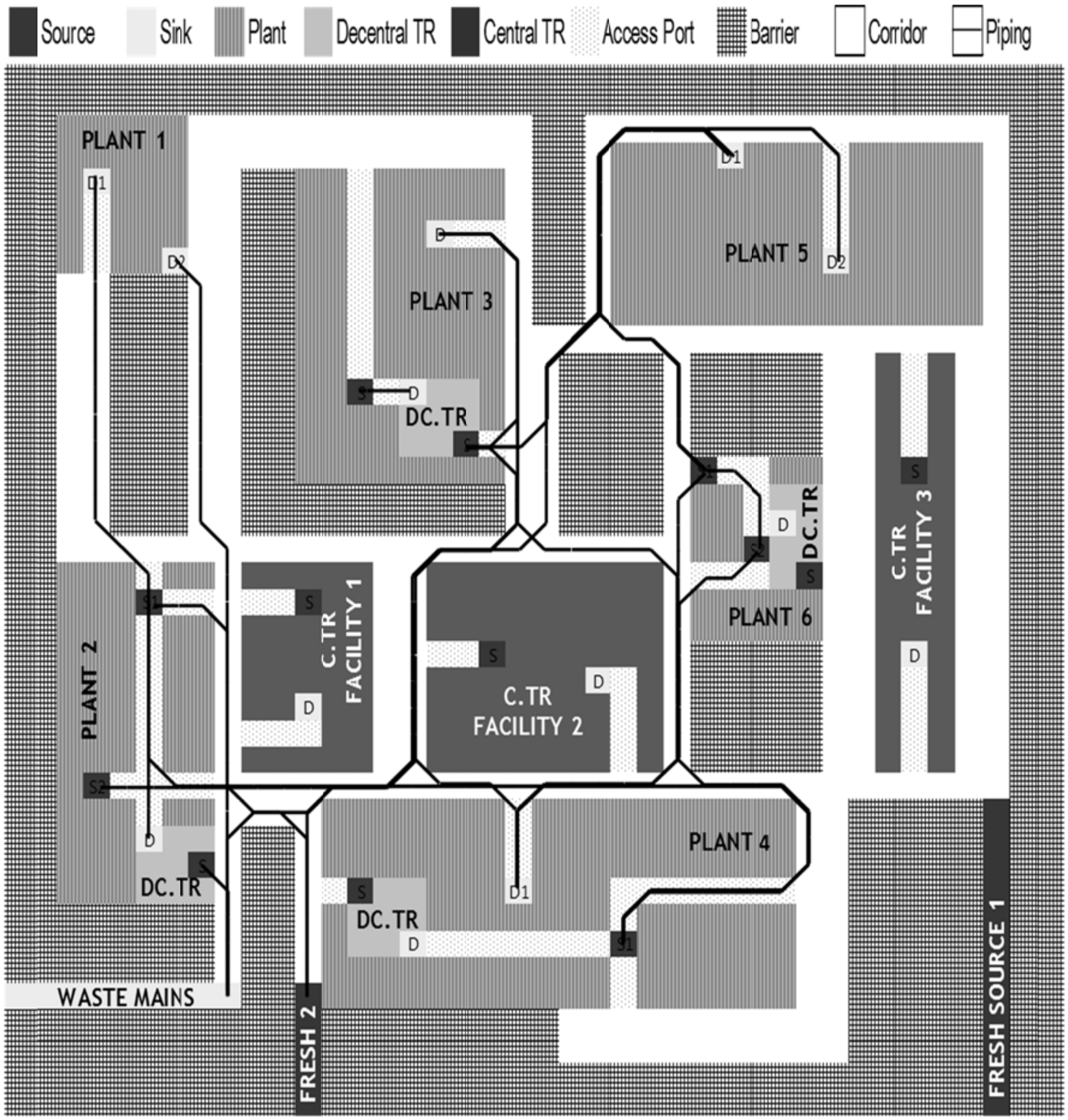

Figure 18. Example Solution Illustrated for Case 10

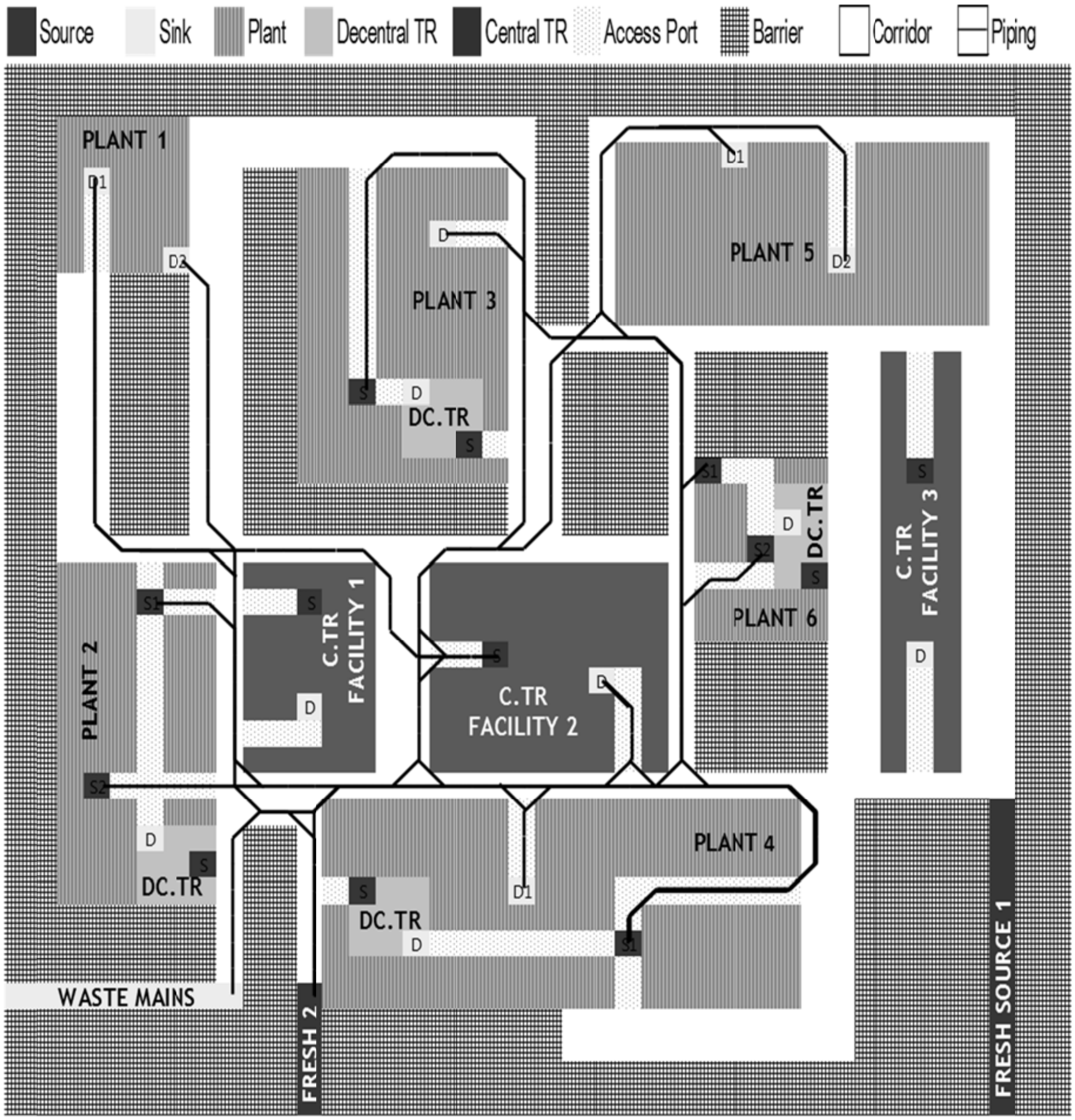

Figure 19. Example Solution Illustrated for Case 10

For all cases that utilized higher-end contaminant data for wastewater sources, infeasibility in obtaining a solution was reported for the cases that only allowed on-site decentral treatment options (ie, Cases 13, 16, 19, 22), as a result of not being able to satisfy the discharge limits imposed on the system. Table 29 provides the optimum cost stream matching for the higher-end single contaminant data cases, when central treatment is enabled only (Cases 14 and 17). Similar to previous implementations involving lower-end pollutant concentration data, the solutions were found to incorporate location 2 for off-site water treatment, and similarly, option 1 was selected for water treatment. However, the most economical results amongst Cases 13-18 were obtained when both on-site and off-site treatment were incorporated (i.e, Cases 15 and 18); the implementation for which is outlined in Table 30, and involves a mix of both centralized and decentralized water treatment. It was also observed that the second freshwater option was also favored for the higher-end single contaminant data. Table 31 provides source-interception-sink stream matching for the optimum cost solution obtained, in which higher-end multiple contaminant data was utilized (Cases 20, 21, 23 and 24). As it has been mentioned, Cases 19 and 22 were reported as infeasible, and thus off-site central treatment was necessary to satisfy all the problem conditions and constraints. The solutions were found to incorporate both freshwater options when higher-end multiple contaminant data were used. Additionally, central off-site treatment location 2 was also selected, which in turn involves option 1 for water treatment.

Comparing the different scenarios involving the two types of piping connectivity, it was observed that cases that utilize Type 2 connectivity were always found to yield more economical piping costs. This also translated to better performing solutions overall when all other costing entities are summed up. However, stream matching and solutions obtained in terms of source-interception-sink implementations were unaffected by the type of connectivity. This was mainly due to constraints imposed on the system, since achieving a viable solution would ultimately depend on the ability to satisfy all the mass balances for water sources, water sinks, and treatment interceptors. Besides, the solutions would need to yield acceptable contaminant concentrations that do not violate any maximum allowable limits, as well as discharge restrictions imposed on the system as a whole.

Table 34 provides a summary for some of the pressure drop values that were obtained amongst all the different connection categories (source-to-sink, source-to-interceptors, interceptors-to-sink, source-to-waste, interceptors-to-waste, and fresh-source). The pressure drops were found to greatly depend on the implementation scenario from the solutions extracted, as well as on the type of piping connectivity enabled. Cases involving Type 2 connectivity were mostly found to yield comparatively lower pressure drop values for the same respective categories. Moreover, the relatively high pressure drops were observed for pipes associated with the most elbows/bends in the network, per unit length of pipe.

Table 34. Summary of pressure drop values

	Right Angled Pathways			Diagonally Integrated Pathways		
	Decentral Treat. Only	Central Treat. Only	Both Enabled	Decentral Treat. Only	Central Treat. Only	Both Enabled
Single Contaminant Considered - Lower End						
Sources-to-Sinks	0.09	0.25	0.09	0.09	0.22	0.09
Sources-to-Int.	1.62	0.00	1.62	1.38	0.00	1.38
Int.-to-Sinks	1.53	0.00	1.53	1.33	0.00	1.33
Sources-to-Waste	4.88	2.73	4.88	4.34	2.55	4.34
Int.-to Waste	1.08	0.00	1.08	0.97	0.00	0.97
Fresh1-Sources	0.00	0.00	0.00	0.00	0.00	0.00
Fresh2-Sources	13.59	2.94	13.59	12.35	2.59	12.35
Multiple Contaminants Considered - Lower End						
Sources-to-Sinks	0.33	1.12	1.12	0.30	1.09	1.09
Sources-to-Int.	0.15	0.93	0.93	0.15	0.78	0.78
Int.-to-Sinks	1.88	1.39	1.39	1.66	1.20	1.20
Sources-to-Waste	1.60	1.12	1.12	1.49	1.04	1.04
Int.-to Waste	1.19	1.79	1.79	1.08	1.56	1.56
Fresh1-Sources	0.00	0.00	0.00	0.00	0.00	0.00
Fresh2-Sources	0.52	13.59	13.59	0.47	12.35	12.35
Single Contaminant Considered - Higher End						
Sources-to-Sinks	-	2.57	5.22	-	2.33	5.07
Sources-to-Int.	-	0.84	0.56	-	0.84	0.56
Int.-to-Sinks	-	1.49	1.06	-	1.49	1.06
Sources-to-Waste	-	6.32	1.26	-	5.88	1.12
Int.-to-Waste	-	2.04	10.08	-	2.03	10.07
Fresh1-Sources	-	0.00	0.00	-	0.00	0.00
Fresh2-Sources	-	6.93	13.59	-	6.93	13.58
Multiple Contaminants Considered - Higher End						
Sources-to-Sinks	-	0.02	0.02	-	0.02	0.02
Sources-to-Int.	-	1.69	1.69	-	1.69	1.69
Int.-to-Sinks	-	1.33	1.33	-	1.33	1.33
Sources-to-Waste	-	0.44	0.44	-	0.41	0.41
Int.-to-Waste	-	3.77	3.77	-	3.77	3.77
Fresh1-Sources	-	5.08	5.08	-	4.76	4.76
Fresh2-Sources	-	13.59	13.59	-	13.58	13.58

III.6. Conclusions

This paper addresses the application of water integration strategies for the synthesis and optimal design of interplant water networks within an industrial city setup, in which centralized and decentralized water treatment options were introduced. Industrial city layouts have been captured according to a similar approach that was introduced in our previous work (Alnouri, Linke et al. 2014a), which enables the exploration of any infrastructure setting for the industrial city in terms of source and sink locations, and available service corridors for water transport. Two different types of wastewater treatment are incorporated, off-site centralized options, as well as on-site decentral arrangements, with pressure drops within pipelines being accounted for. Hence, this work introduces an approach that helps decision-makers systematically explore various wastewater treatment and reuse scenarios amongst a cluster of plants.

Developing efficient strategies for wastewater disposal ultimately entails an integrated understanding of potential consequences on public health, agricultural practices, as well as other environmental concerns. For these reasons, some industrial cities are starting to enforce policies that involve Zero Liquid Discharge (ZLD) practices for wastewater disposal. Currently, ZLD aspects were not part of the proposed methodology; however, these additional considerations could certainly be the subject of future work. Additionally, addressing interconnectivity scenarios for wastewater treatment and reuse networks by introducing pipeline merging options have not been accounted for in this work; hence, introducing such design aspects into the problem could also be investigated.

CHAPTER IV

OPTIMAL INTERPLANT WATER NETWORKS FOR INDUSTRIAL ZONES: ADDRESSING INTERCONNECTIVITY OPTIONS THROUGH PIPELINE MERGING*

To date, alternative design options that exist for interconnecting transmission and distribution networks have not been considered in water reuse network synthesis. Existing approaches that do incorporate piping expenses in the design of interplant water networks assign a separate pipeline for every water allocation. However, merging together common pipeline regions for the transmission of water from, or to nearby but different processing facility destinations may improve the overall water network performance not only in terms of cost efficiency but also in terms of complexity. This paper introduces a novel approach that is capable of accounting for pipeline merging scenarios that could exist within a water reuse network. Two different pipeline branching possibilities have been introduced in this work, for the purpose of merging: (1) forward branching, and (2) backward branching. The approach is implemented for the design of interplant water networks considering direct water re-use amongst several coexisting processing facilities within an industrial zone. A case study is presented to illustrate the application of the approach and its benefits.

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IV.1. Introduction

Water integration methodologies offer reliable tools for identifying optimal wastewater reuse strategies that would allow industries to minimize their water footprints, either individually (in-plant integration) or collectively (inter-plant integration). Many water integration approaches have been developed and successfully applied with a strong focus on water integration in individual plants or facilities.

Early work by Wang and Smith (1994a, 1994b) led to the water pinch analysis approach that provides insight regarding potential opportunities for wastewater minimization in process industries. Olesen and Polley (1996) introduced a simple adaptation of the methodology in which additional constraints were incorporated into the water network design problem, in terms of the plant's geographical location, as well as the piping costs involved. Alva-Argáez et al. (1998) developed a superstructure optimization model that includes all the possible features of a water network design, using a recursive decomposition scheme that combines insights from water-pinch analysis together with mathematical programming. Savelski and Bagajewicz (2000) introduced a design methodology for water-using networks in processing plants, by investigating the necessary optimality conditions for a water allocation problem involving a single contaminant. El-Halwagi et al. (2003) utilized insightful mixing and segregation principles to develop a rigorous graphical targeting approach for minimizing the overall freshwater consumption within a process by means of direct recycling schemes. Manan et al. (2004) developed a water cascade analysis technique to establish the minimum water and wastewater targets for the synthesis and design of water networks. Prakash and Shenoy (2005) presented an algorithm to design minimum freshwater networks for fixed flowrate problems, based on the principle of having source streams with the nearest contaminant concentrations being chosen to satisfy a particular water demand. Liu et al. (2007) proposed a new method to determine the pinch points and freshwater targets for water-using networks involving a single contaminant, based on the characteristics of the pinch point in the problem, before carrying out any targeting calculations. Hu et al. (2011) studied the effect of different process decomposition strategies on freshwater savings, using concentration–mass load diagrams. Lee et al. (2013b) explored chilled water reuse and recycle opportunities using a superstructure approach that accounts for all possible network connections, and a conflicting objective was utilized to reduce network complexity, and improve flexibility within the solutions obtained. Chaturvedi and Bandyopadhyay (2014) proposed a multi-objective mixed integer linear programming formulation that simultaneously targets minimum fresh water utilization, and maximum production in a batch process. A Pareto optimal front was used to investigate trade-offs between production and fresh flows within the system.

Other contributions expanded existing water integration approaches by considering wastewater reuse amongst an existing cluster of processing facilities, which is referred to as interplant water integration. Liao et al. (2007) investigated the design of flexible interplant water networks by combining mathematical programming techniques with pinch analysis insights. Lovelady and El-Halwagi (2009) utilized a source-interception-sink representation to develop an optimization-based approach for water allocation amongst multiple processes within a shared eco-industrial facility. Chen et al.

(2010) presented a novel integration scheme for inter-plant water integration within an industrial complex, in which both centralized and decentralized water mains were used to connect the water-using units within the individual plants. Aviso et al. (2010a, 2010b) utilized fuzzy mathematical programming techniques to identify optimal network designs that maximize wastewater reuse amongst a cluster of plants. Chew et al. (2010a, 2010b) introduced a new algorithm for targeting minimum fresh and waste flowrates for interplant resource conservation problems, which can also be applied for the design of water networks. Rubio-Castro et al. (2011) developed a global optimal formulation for water integration in eco-industrial parks, based on a superstructure that allows the wastewater reuse within the same plant, as well as water exchange amongst different plants. Additionally, Rubio-Castro et al. (2012) utilized a MINLP model to retrofit existing water networks from different plants within the same industrial zone, by accounting for both intra-plant and inter-plant structural modifications. Boix et al. (2012) formulated a Mixed-Integer Linear Programming problem based on the necessary conditions of optimality defined by Savelski and Bagajewicz (2000), for designing an Eco-Industrial Park (EIP) using three different EIP regeneration scenarios. Lee et al. (2013a) introduced a mathematical optimization model involving a two-stage approach, for inter-plant water network synthesis in which the individual processing units operate in a mix of both continuous and batch modes. More recently, Alnouri et al. (2014a) introduced a spatial representation for the design of interplant water networks within industrial zones, whilst accounting for optimum routing strategies for water allocation, by considering the layout of assigned corridor regions that available for water transport.

The work was then extended to account for the presence of centralized and decentralized wastewater treatment locations, as possible interception options, before water reuse (2014b). It was found that the design of water pipeline networks that achieve interplant integration certainly depends on the topography of an industrial zone; in terms of how the various plants and their respective processing facilities are arranged.

To date, all work has considered network connections between water sources and sinks are segregated, i.e. one pipeline is associated with each connection. No work has been proposed to consider the interconnectivity options that exist for a network as a result of merging interconnecting water pipelines to reduce network complexity and capitalize on potential economies of scale. In terms of studies that involve the design of efficient pipeline networks, most contributions have been made regarding the design of gas pipelines. For instance, Wong and Larson (1968) applied dynamic programming techniques to determine the optimal operating conditions for and unbranched natural gas pipeline. Graham et al. (1971) performed studies on a single-phase gas network, and utilized steady-state flow and pressure distribution conditions when optimizing the design of the gas pipeline network. Flanigan (1972) conducted a series of optimization problems, using the generalized reduced gradient method, for the design of optimal compressor sizes and pipeline diameters on a pre-selected network configuration. Baskaran and Salzborn (1979) studied the problem of designing gas pipeline collection networks in a desert environment, in which no physical obstacles were considered. An efficient method for determining optimal positioning of pipeline junction points, and the respective diameter of the pipes was presented. Olorunniwo and Jensen (1982a,1982b) developed a methodology that accounts for capacity expansion in natural gas transmission networks. Almisned and and Alkahtani (1996) studied the design of an optimal pipeline network for transporting natural gas amongst GCC countries. Their study takes into account the type of fluid, transportation distances, location, and topography for determining all the optimization criteria required for the pipeline network. Amado (2011) introduced a new modeling approach for multi-commodity network flow schemes that can be utilized for sequencing refined products in pipeline systems. The overall design of the pipeline system is capable of generating the optimal sequences of batches of products and their destination, as well as the amount of product to be pumped, while satisfying the product demands. Bonnas et al.(2011) developed a methodology for the design pipe networks via global optimization. Their study involved the investigation of a gas network optimization problem, based on the hypothesis of a stationary flow.

Enabling water reuse strategies within industrial zones requires an effective synthesis and design strategy for pipeline networks to implement interplant water transmission and distribution. Network cost is always considered a key item that would determine the viability of a developed network design. Existing water integration methods do not consider the pipeline aspect of the water network design in depth, even though a great portion of the network's total expenses would usually involve pipeline construction and maintenance costs. So far, problems involving the design of water networks associate a separate standalone pipeline with every water allocation. Such an implementation is likely not practical, especially within a typical multi-stakeholder setting. In a first effort towards overcoming these limitations, this paper presents a novel approach to exploring interplant water integration whilst considering less complex interconnecting networks with merged segments. So far, all research contributions that involve interplant water network design do not incorporate such merged pipeline options as a design possibility within the network. Section 2 of this paper describes the synthesis problem, Section 3 outlines the methodology that has been adopted, Section 4 details the mathematical formulation, and Section 5 provides a case study illustration.

IV.2. Background and Synthesis Problem

Pipelines are the prevalent infrastructures to facilitate low-cost material exchange across processing locations. The pipeline construction costs depend on the material of construction, diameter and length of the pipeline being assembled and their implementation (surface or buried).Parallel pipelines of small diameters are typically more expensive to construct, maintain and operate compared to large diameter pipelines conveying the same water flow. The design of effective and cost efficient pipeline networks for interplant water transmission and distribution is very important, because economics and complexity play an important role in the development of sustainable strategies for water reuse. The exploration of pipeline design alternatives within the boundaries of industrial zones is necessary to identify effective solutions from the different options that exist for assembling interconnecting networks.

Even though existing interplant water integration methods may reveal substantial water savings through wastewater reuse amongst an existing cluster of plants, water transmission via pipelines is often a major cost item. A typical output of a water integration approach considers each source-sink interconnection to constitute a separate pipeline (Figure 20).

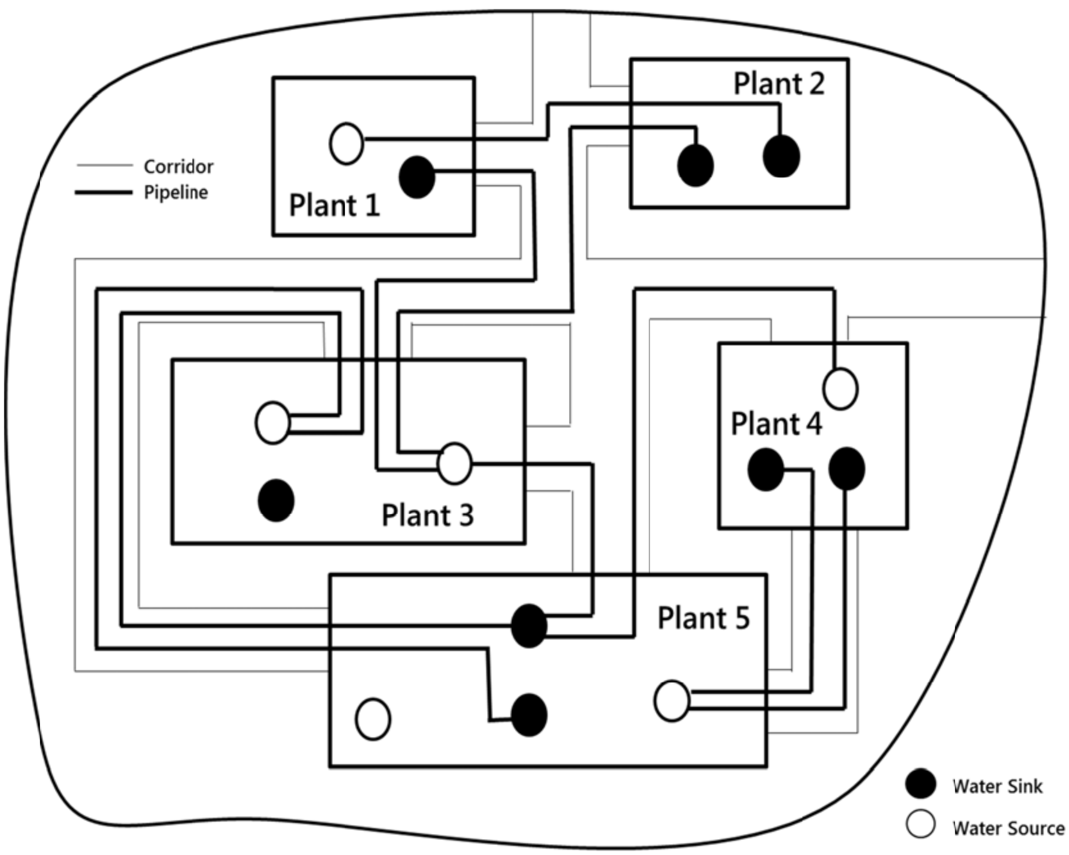

Figure 20. Typical output of a source-sink mapping activity, for the design of interplant water networks

Given the spatial layout of an industrial zone with the requirements to maintain pipelines within defined corridor regions (Alnouri, Linke et al. 2014a), parallel pipelines can be expected to emerge when implementing optimal water reuse allocations amongst a cluster of plants. Moreover, the stakeholders responsible for the development of water networks across an industrial zone are typically different entities from the ones owning or operating the facilities within the city. Therefore, a pipeline network to be implemented in such a multi-stakeholder setting would require acceptably low complexity which is unlikely to be achieved if each source-sink connection would require a separate pipeline.

The complexity of a water network design could often be reduced through fewer connections, by identifying pipelines with common segments that are transporting water of similar quality to different but relatively close destinations. Moreover, substantial economies of scale are often achieved when transporting materials in bulk. These economies of scale typically result in low operating costs, when compared to the construction costs entailed. Pipelines are often attributed with the ability to effectively transport large quantities of material from one location to another, since a slight increase in the diameter of a pipeline can exponentially enhance its respective transportation capacity. This makes it more efficient to build one large pipeline rather than two or more small pipelines in many situations. Moreover, networks involving relatively larger pipelines are often easier to operate and maintain, and their governance simplifies when fewer pipes and segments are involved. On the other hand, it might in some cases be more economical to build parallel piping arrangements for smaller systems that do not require high transmission capacities or where water qualities significantly differ.

The identification of low cost pipeline networks for a given industrial zone water integration challenge requires the ability to represent and assess the various possible network options. Given that existing approaches only consider water networks with segregated source-sink connecting pipelines, the purpose of this work is to develop a representation for use in water integration that is capable of capturing the opportunities for merging pipelines so as to enable the screening of less complex pipeline networks in the course of determining optimal water integration strategies. The efficiency of implementing merged pipeline scenarios is compared to results from previous work (Alnouri, Linke et al. 2014a), which assigns a separate pipeline for each water allocation.

IV.3. Methodology

As mentioned above, all current approaches that involve synthesis and design of water networks associate a separate pipeline with every water allocation. We refer to an 'unmerged connectivity' when we describe such networks. This section presents a methodology to enable the design of water networks whilst incorporating merged pipeline transmission options, amongst several coexisting processing facilities within an industrial zone. For the purpose of keeping the methodology illustration relatively simple in this paper, this work considers the case of direct water re-use to achieve water integration across plants in an industrial zone. However, it should be noted that the same principles that are introduced in this paper can be extended and applied for cases in which water regeneration and reuse strategies are explored for water integration.

A strategy for the systematic development of pipeline merging and assembling strategies in interplant water networks is required to capture alternative pipeline network options. We first identify the different types connectivity involved within the network for direct water reuse: (a) source-to-sink, (b) fresh-to-source, and (c) sink-to-waste. For a given water source (or freshwater source) feeding into multiple sinks, a common unmerged interconnectivity scenario would usually involve separate pipelines to the individual water sinks, as illustrated in Figure 12. Similarly, for a given water sink (or wastewater discharge sink), an unmerged scenario would involve water being received from several water sources, as illustrated in Figure 22.

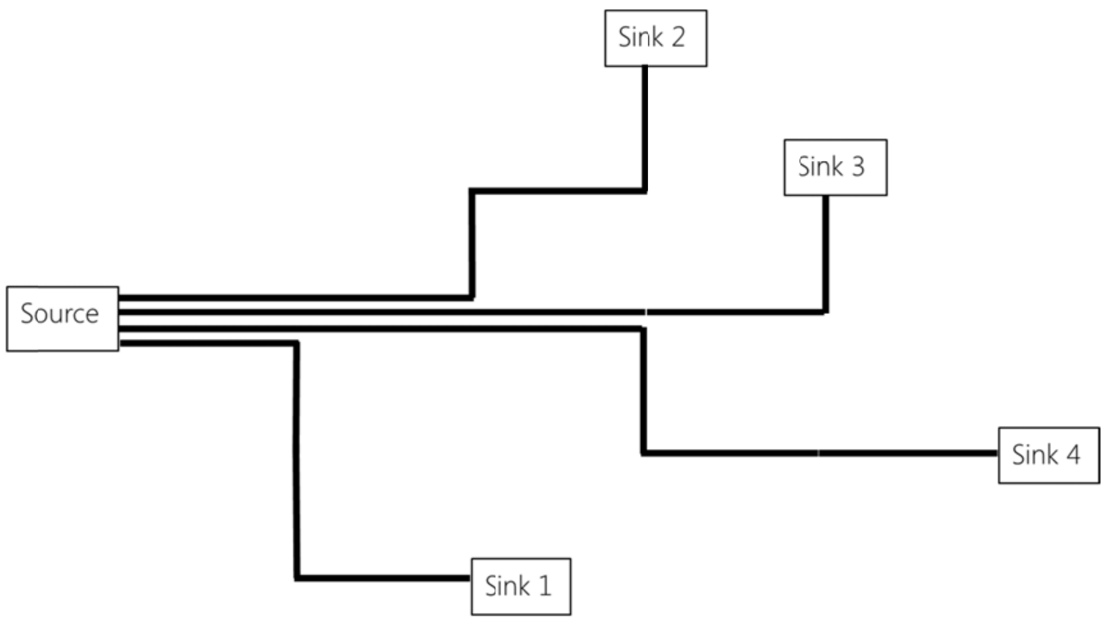

Figure 21. An unmerged pipeline connectivity demonstration for a given water source, distributing water to several nearby water sinks

Merging pipelines can result in various stream mixing options. Such mixing of wastewater streams with different qualities might hinder their usage in a number of potential water sinks, when mixed in the same pipeline with other water streams with different contamination levels. This can be avoided with a merging scenario that yields no change in quality, compared to the case of being transported in a separate pipe scenario; hence, the merged pipeline will be associated with a uniform water quality.

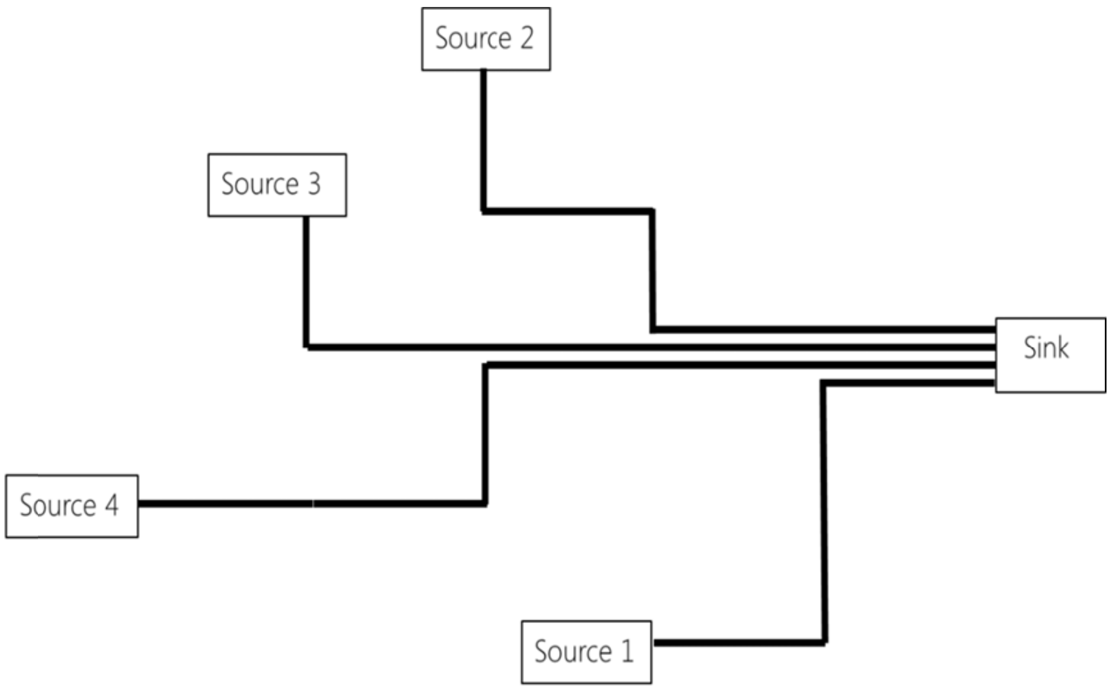

Figure 22. An unmerged pipeline connectivity demonstration for a given water sink, receiving water from several nearby water sources

This case considers only pipelines that originate from same water source location to be merged together. Similarly, pipelines to the same water sink destination can also be merged without undesired mixing. The two merging options lead to two different pipeline branching schemes that could be adopted, whilst avoiding any mixing in between water qualities within the pipelines.

IV.3.1 Forward Branching Scheme

This scheme involves a given water source (or freshwater mains) being distributed to several nearby water sinks. Figure 23 illustrates the concept of forward branching to determine merged pipeline segments. The pipeline is constructed using relatively larger diameters at the very beginning of the transmission, and narrows down to smaller diameters to accommodate the changes in flow rates from section to section. The forward branching applies to source-to-sink and fresh-to source connectivity categories.

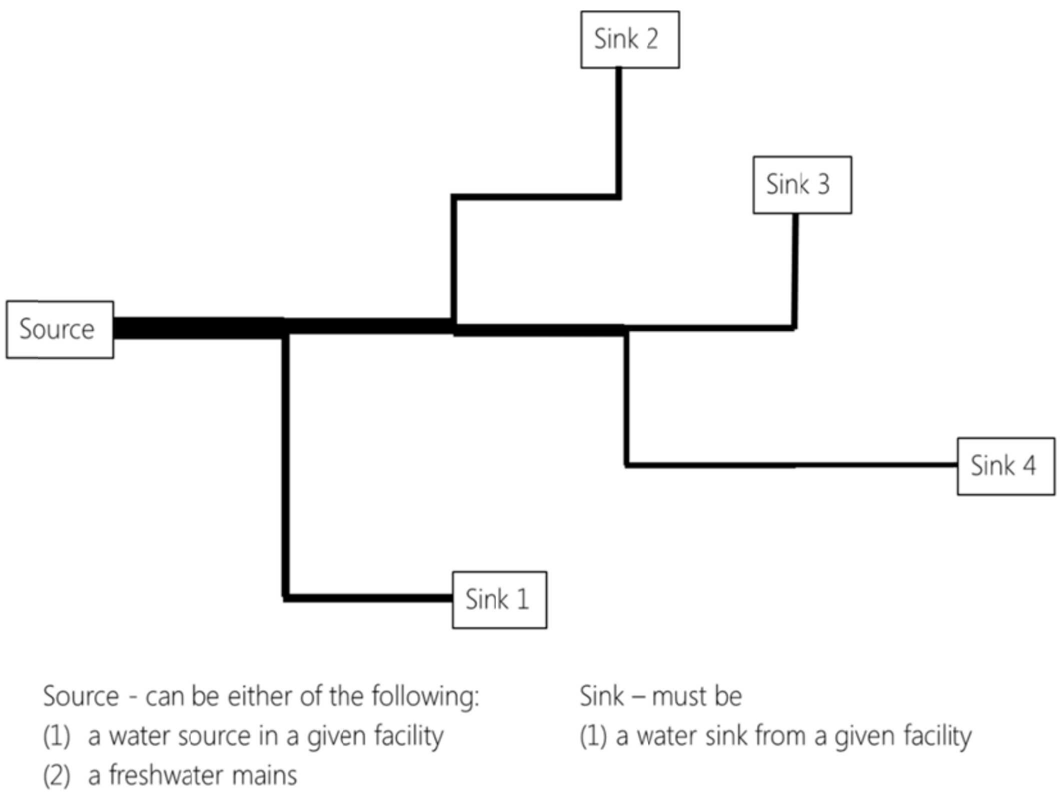

Figure 23. A merged pipeline connectivity demonstration via forward branching, for a given water source, distributing water to several nearby water sinks

IV.3.2 Backward Branching Scheme

This scheme involves water from several nearby water sources being collectively transmitted to a given water sink (or wastewater discharge mains). Figure 24 illustrates the concept of backward branching to determine merged pipeline segments. The pipeline is constructed using relatively smaller diameters at the beginning of the transmission, and increases to larger diameters as flows increase. Backward branching applies to source-to-sink, and sink-to-waste connectivity categories.

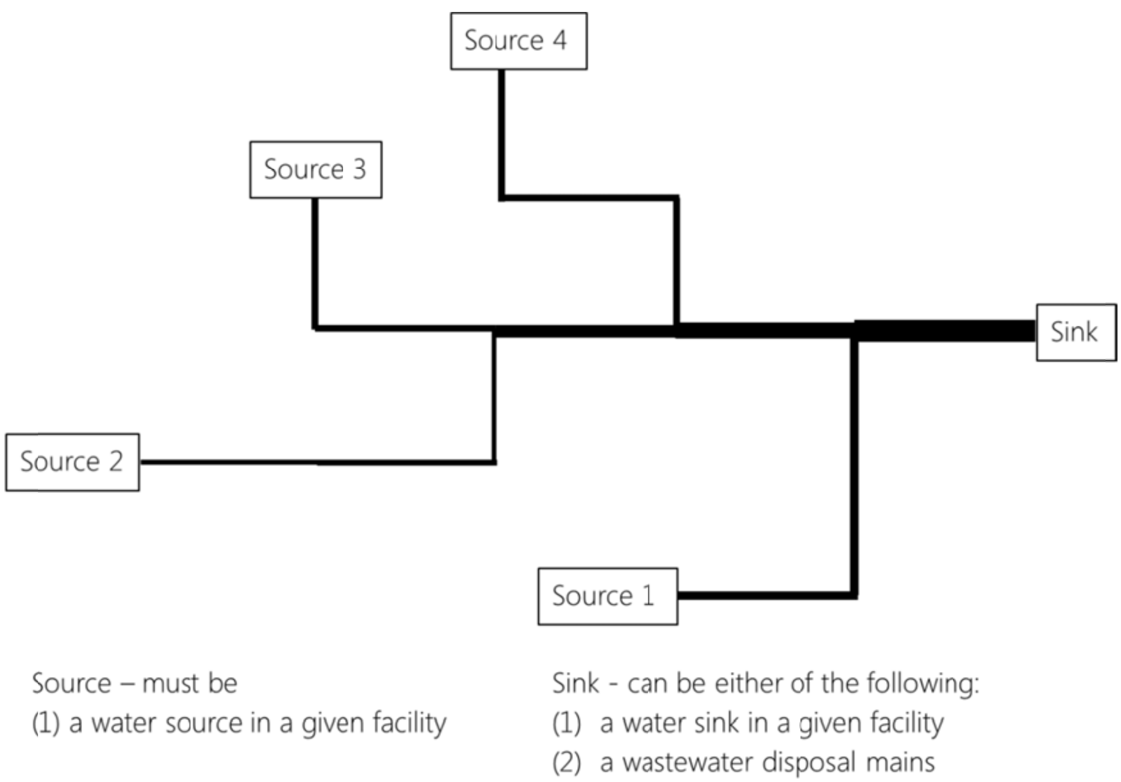

Figure 24. A merged pipeline connectivity demonstration via backward branching, for a given water sink, receiving water from several nearby water sources

Figures 23 and 24 show that regardless of the branching scheme that is selected for assembling a merged pipeline, both options share several common characteristics. Merged pipelines feature nodes that connect the various branches together, with each node intersection resulting in a flow and size (diameter) change. Hence, every pipeline branch is defined between two consecutive nodes, and is associated with a different size when compared to both preceding and subsequent branches. In this work, all pipeline nodes have been defined according to levels, which are named according to the degree of branching involved. For instance, first level nodes consist of the first set of nodes that form pipelines braches, and have no preceding nodes within the pipeline, except the starting point, whereas a second level node would originate from a preceding first level node and so on. Figure 25 illustrates the node level classification procedure that has been followed which defines the endpoints of the various segments or branches within a merged pipeline. All first level branches in the pipeline are formed by connecting the point(s) from which the pipeline originates to the different first level nodes that exist within the pipeline. Similarly, All second level branches in the pipeline are formed by connecting first level nodes to second level nodes that exist within the pipeline. In case further branching is considered, third level nodes would then form another set of third branches, by connecting to third level nodes. The procedure is repeated until the different node levels consistently connect to successive levels, and keep forming new sets of pipeline branches, up until reaching the destination point(s).

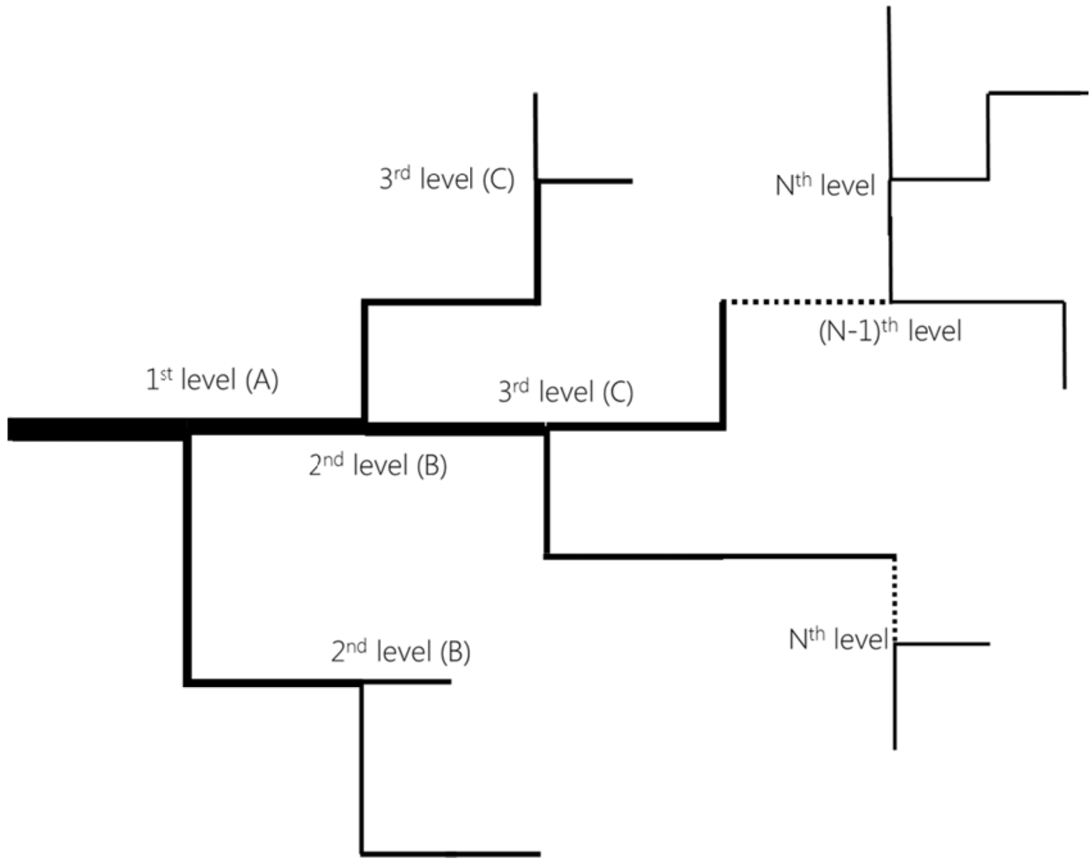

Figure 25. Node level illustration (for both forward and backward branching)

IV.4. Problem Statement and Mathematical Formulation

The problem statement can be summarized as follows. Given an industrial zone consisting of a cluster of plants P, each containing its own set of water sources SU_p and water sinks SN_p, it is required to develop a strategy for optimal water reuse across the different water processes subject to minimizing the total piping and freshwater costs of the interplant water network design. In this work, the optimal solutions are sought for a direct water reuse strategy that achieves a cost-optimal network, while taking into account the various pipeline merging scenarios that could be incorporated into the network design, for interplant water transmission and distribution. The objective function is specified as:

$$
\begin{aligned}
&Minimize.\ \ \gamma\Bigg[\sum\sum\sum\sum\nolimits_{p\in P\ i\in SU_p j\in SN_p a\in X_{ip,jp'}} \alpha\left(DI^{a}_{ip,jp'}\right)^{\beta} L^{a}_{ip,jp'} \\
&+\sum\sum\sum\nolimits_{p\in P\ i\in SU_p a\in X_{ip}} \alpha\left(DI^{a}_{ip}\right)^{\beta} L^{a}_{ip} \\
&+\sum_{p\in P}\sum_{j\in SN_p}\sum_{a\in X_{jp}} \alpha\left(DI^{a}_{jp}\right)^{\beta} L^{a}_{jp} + \sum\sum\sum\sum\nolimits_{p\in P\ i\in SU_p j\in SN_p a\in X_{ip,jp'}\ b\in Y_{ip,jp'}} \alpha\left(DI^{a,b}_{ip,jp'}\right)^{\beta} L^{a,b}_{ip,jp'} \\
&+\sum\sum\sum\nolimits_{p\in P\ i\in SU_p a\in X_{ip}\ b\in Y_{ip}} \alpha\left(DI^{a,b}_{ip}\right)^{\beta} L^{a,b}_{ip} + \sum_{p\in P}\sum_{j\in SN_p}\sum_{a\in X_{jp}\ b\in Y_{jp}} \alpha\left(DI^{a,b}_{jp}\right)^{\beta} L^{a,b}_{jp} \\
&+\sum\sum\sum\sum\nolimits_{p\in P\ i\in SU_p j\in SN_p\ a\in X_{ip,jp'}\ b\in Y_{ip,jp'}\ c\in Z_{ip,jp'}} \alpha\left(DI^{a,b,c}_{ip,jp'}\right)^{\beta} L^{a,b,c}_{ip,jp'} \\
&+\sum\sum\sum\nolimits_{p\in P\ i\in SU_p a\in X_{ip}\ b\in Y_{ip}\ c\in Z_{ip}} \alpha\left(DI^{a,b,c}_{ip}\right)^{\beta} L^{a,b,c}_{ip} \\
&+\sum_{p\in P}\sum_{j\in SN_p}\sum_{a\in X_{jp}\ b\in Y_{jp}\ c\in Z_{jp}} \alpha\left(DI^{a,b,c}_{jp}\right)^{\beta} L^{a,b,c}_{jp} + \cdots \\
&+\sum\sum\sum\sum\nolimits_{p\in P\ i\in SU_p j\in SN_p\ a\in X_{ip,jp'}\ b\in Y_{ip,jp'}\ c\in Z_{ip,jp'}\ldots(n-1)\in(N-1)_{ip,jp'}\ n\in N_{ip.jp'}} \alpha\left(DI^{a,b,c,..,n-1,n}_{ip,jp'}\right)^{\beta} L^{a,b,c,..,n-1,n}_{ip,jp'} \\
&+\sum\sum\sum\nolimits_{p\in P\ i\in SU_p a\in X_{ip}\ b\in Y_{ip}\ c\in Z_{ip}\ldots(n-1)\in(N-1)_{ip}\ n\in N_{ip}} \alpha\left(DI^{a,b,c,..,n-1,n}_{ip}\right)^{\beta} L^{a,b,c,..,n-1,n}_{ip} \\
&+\sum_{p\in P}\sum_{j\in SN_p}\sum_{a\in X_{jp}\ b\in Y_{jp}\ c\in Z_{jp}\ldots(n-1)\in(N-1)_{jp}\ n\in N_{jp}} \alpha\left(DI^{a,b,c,..,n-1,n}_{jp}\right)^{\beta} L^{a,b,c,..,n-1,n}_{jp}\Bigg] \\
&+H_y C^{FRESH}\sum_{p\in P}\sum_{j\in SN_p} F_{jp}
\end{aligned}
\tag{77}
$$

The water integration problem is subject to a number of constraints that involve total mass balances around all water sources (Equation (78)) and sinks (Equation (79)), in which the individual flow terms must equal all given water source flows (W_{ip}), and the specified sink flows (G_{jp}) respectively. Additionally, the network is also subject to component mass balances around the water sinks, as described by Equation (80).

Equation (81) sets limits on the allowable sink contaminant range, according to the maximum and minimum pollutant limits that are allowed into each sink. Additionally, Equations (82)-(84) associate all flowrate variables with a non-negativity condition. Equations (78)-(84) were all based on direct water reuse formulations.

$$\sum\sum_{p\in P\ j\in SN_p} M_{ip,jp'} + D_{ip} = W_{ip} \quad \forall p,p' \in P \quad \forall i \in SU_p \tag{78}$$

$$\sum\sum_{p\in P\ i\in SU_p} M_{ip,jp'} + F_{jp} = G_{jp} \quad \forall p,p' \in P \quad \forall j \in SN_p \tag{79}$$

$$\sum\sum_{p\in P\ i\in SU_p} M_{ip,jp'}\, x_{c,ip}^{Source} + F_{jp} x_c{}^{FRESH} = G_{jp} z_{c,jp}^{in}$$

$$\forall p,p' \in P;\ \ \forall j \in SN_p\ ;\ \forall c \in C \tag{80}$$

$$z_{c,jp}^{min} \leq z_{c,jp}^{in} \leq z_{c,jp}^{max} \tag{81}$$

$$M_{ip,jp'} \geq 0 \qquad \forall p,p' \in P\ ;\ \forall j \in SN_p\ ; \forall i \in SU_p \tag{82}$$

$$D_{ip} \geq 0 \qquad \forall p \in P;\ \forall i \in SU_p \tag{83}$$

$$F_{jp} \geq 0 \qquad \forall p \in P\ ;\ \forall j \in SN_p \tag{84}$$

Additionally, pipe diameters are calculated using Equation (85), according to the recommended velocity ranges by Peters et al. (2003), using the mass flowrate (kg/s) of each respective stream. All diameters were then rounded up to the nearest size, so as to reflect the use of a standardized, instead of customized pipe sizes.

$$DI = Roundup\left[0.363\left(\left(\frac{Flow}{\rho}\right)^{0.45}\ \rho^{0.13}\right)\right] \tag{85}$$

In addition to the above source-sink mapping formulation for direct water reuse, the constraints relating to pipeline merged segments are derived below. Each merging scenario can is implemented separately.

IV.4.1 Forward Branching Formulation

Equations (86)-(111) below detail the mathematical formulation associated with a forward branching scheme in a pipeline.

The flow allocated from source i in plant p to sink j in plant p' ($M_{ip,jp'}$) must equal the summation of all flows ($M_{ip,jp'}^{a}$) from the various branches that connect source i in plant p to all 1st level nodes a, associated with the stream connection.

$$\sum_{a=1}^{X_{ip,jp'}} M_{ip,jp'}^{a} = M_{ip,jp'} \quad \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p, p' \in P \tag{86}$$

The flow allocated from the freshwater mains to sink j in plant p' (F_{jp})must equal the summation of all flows $\left(F_{jp}^{a}\right)$from the various branches that connect the fresh mains to all 1st level nodes a, associated with the stream connection.

$$\sum_{a=1}^{X_{jp}} F_{jp}^{a} = F_{jp} \quad \forall j \in SN_p;\ \forall p \in P \tag{87}$$

The flows allocated from each of the 1st level nodes in the stream that connects source i in plant p to sink j in plant p' ($M_{ip,jp'}^{a}$) must equal the summation of all flows ($M_{ip,jp'}^{a}$) from the various branches that connect each 1st level node a, to all 2nd level nodes *b* associated with the stream connection.

$$\sum_{b=1}^{Y_{ip,jp'}} M_{ip,jp'}^{a,b} = M_{ip,jp'}^{a} \quad \forall a \in X_{ip,jp'}\,; \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p, p' \in P \tag{88}$$

The flows allocated from each of the 1st level nodes in the stream that connects the freshwater mains to sink j in plant p' (F_{jp}^{a}) must equal the summation of all flows ($F_{jp}^{a,b}$) from the various branches that connect each 1st level node a, to all 2nd level nodes b associated with the stream connection.

$\sum_{b=1}^{Y_{jp}} F_{jp}^{a,b} = F_{jp}^{a} \quad \forall a \in X_{jp}\ ;\ \forall j \in SN_p;\ \forall p \in P$ (89)

The flows allocated from each of the 2nd level nodes in the stream that connects source i in plant p to sink j in plant p' ($M_{ip,jp'}^{a,b}$) must equal the summation of all flows ($M_{ip,jp'}^{a,b,c}$) from the various branches that connect each 2nd level node *b*, to all 3rd level nodes *c* associated with the stream connection.

$\sum_{c=1}^{Z_{ip,jp'}} M_{ip,jp'}^{a,b,c} = M_{ip,jp'}^{a,b}$

$\forall a \in X_{ip,jp'};\ \forall b \in Y_{ip,jp'}\ ; \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p, p' \in \mathrm{P}$ (90)

The flows allocated from each of the 2nd level nodes in the stream that connects the freshwater mains to sink j in plant p' ($F_{jp}^{a,b}$) must equal the summation of all flows ($F_{jp}^{a,b,c}$) from the various branches that connect each 2nd level node *b*, to all 3rd level nodes *c* associated with the stream connection.

$\sum_{c=1}^{Z_{jp}} F_{jp}^{a,b,c} = F_{jp}^{a,b} \quad \forall a \in X_{jp}\ ;\ \forall b \in Y_{jp}\ ; \forall j \in SN_p;\ \forall p \in P$ (91)

The flows allocated from each of the (n-1)th level nodes in the stream that connects source i in plant p to sink j in plant p' ($M_{ip,jp'}^{a,b,c,..,n-1}$) must equal the summation of all flows ($M_{ip,jp'}^{a,b,c,..,n}$) from the various branches that connect each (n-1)th level node, to all nth level nodes associated with the stream connection.

$\sum_{n=1}^{N_{ip,jp'}} M_{ip,jp'}^{a,b,c,..,n-1,n} = M_{ip,jp'}^{a,b,c,..,n-1} \quad \forall a \in X_{ip,jp'};\ \forall b \in Y_{ip,jp'}\ ; \forall c \in Z_{ip,jp'} \ldots \forall (n - 1) \in (N-1)_{ip,jp'}; \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p, p' \in P$

(92)

The flows allocated from each of the (n-1)th level nodes in the stream that connects the freshwater mains to sink j in plant p' ($F_{jp}^{a,b,c,..,n-1}$) must equal the summation of all flows ($F_{jp}^{a,b,c,..,n-1,n}$) from the various branches that connect each (n-1)th level node, to all nth level nodes associated with the stream connection.

$$\sum_{n=1}^{N_{jp}} F_{jp}^{a,b,c,..,n-1,n} = F_{jp}^{a,b,c,..,n-1} \quad \forall a \in X_{jp}\,;\ \forall b \in Y_{jp}\,; \forall c \in Z_{jp} \,..\, \forall (n-1) \in (N-1)_{jp};\ \forall j \in SN_p;\ \forall p \in P \tag{93}$$

The flow from a source i in plant p to a 1st level node *a* that eventually connects to sink j in plant p' ($M_{ip,jp'}^{a}$) must be equal to the flow associated with the same 1st level node *a* connecting source i in plant p to any other sink j' in plant p'' ($M_{ip,j'p''}^{a}$).

$$M_{ip,jp'}^{a} = M_{ip,j'p''}^{a}\, \forall i \in SU_p;\ \forall (j,j') \in SN_p;\ \forall (p,p',p'') \in P; \forall a \in X_{ip,jp'} \tag{94}$$

The flow from the freshwater mains to a 1st level node *a* that eventually connects to sink j in plant p' (F_{jp}^{a}) must be equal to the flow associated with the same 1st level node *a* connecting the freshwater mains to any other sink j' in plant p' ($F_{j',p'}^{a}$).

$$F_{jp}^{a} = F_{j',p'}^{a}\, \forall (j,j') \in SN_p;\ \forall (p,p') \in P; \forall a \in X_{jp} \tag{95}$$

The flow from a source i in plant p to a 2nd level node *b* through a 1st level node *a* that eventually connects to sink j in plant p' ($M_{ip,jp'}^{a,b}$) must be equal to the flow associated with that 2nd level node *b* through the same 1st level node *a* connecting source i in plant p to any other sink j' in plant p'' ($M_{ip,j'p''}^{a,b}$).

$M_{ip,jp'}^{a,b} = M_{ip,j'p''}^{a,b}, \forall i \in SU_p;\ \forall (j,j') \in SN_p;\ \forall (p,p',p'') \in P; \forall a \in X_{ip,jp'};\ \forall b \in Y_{ip,jp'}$ (96)

The flow from the freshwater mains to a 2nd level node b through a 1st level node a that eventually connects to sink j in plant p' ($F_{jp}^{a,b}$) must be equal to the flow associated with that 2nd level node b through the same 1st level node a connecting the freshwater mains to any other sink j' in plant p'($F_{j',p'}^{a,b}$).

$F_{jp}^{a,b} = F_{j',p'}^{a,b}\ \forall (j,j') \in SN_p;\ \forall (p,p') \in P; \forall a \in X_{jp}; \forall b \in Y_{jp}$ (97)

The flow from a source i in plant p to a 3rd level node *c* through a 2nd level node *b* and a 1st level node *a* that eventually connects to sink j in plant p' ($M_{ip,jp'}^{a,b,c}$) must be equal to the flow associated with that 3rd level node *c* through the same 2nd level node *b* and 1st level node *a* connecting source i in plant p to any other sink j' in plant p''($M_{ip,j'p''}^{a,b,c}$).

$M_{ip,jp'}^{a,b,c} = M_{ip,j'p''}^{a,b,c}, \forall i \in SU_p;\ \forall (j,j') \in SN_p;\ \forall (p,p',p'') \in P; \forall a \in X_{ip,jp'};\ \forall b \in Y_{ip,jp'};\ \forall c \in Z_{ip,jp'}$ (98)

The flow from the freshwater mains to a 3rd level node *c* through a 2nd level node *b* and a 1st level node *a* that eventually connects to sink j in plant p' ($F_{jp}^{a,b,c}$) must be equal to the flow associated with that 3rd level node *c* through the same 2nd level node *b* and 1st level node *a* connecting the freshwater mains to any other sink j' in plant p'($F_{j',p'}^{a,b,c}$).

$$F_{jp}^{a,b,c} = F_{j\prime,p\prime}^{a,b,c}\ \forall (j,j') \in SN_p;\ \forall (p,p') \in P; \forall a \in X_{jp}; \forall b \in Y_{ip,jp'}; \forall c \in Z_{ip,jp'} \tag{99}$$

The flow from a source i in plant p to an n^{th} level node *n* through an $(n-1)^{th}$ level node *(n-1)* all the way to a 1^{st} level node *a* that eventually connects to sink j in plant p' ($M_{ip,jp\prime}^{a,b,c,..,n-1,n}$) must be equal to the flow associated with that n^{th} level node *n* through the same $(n-1)^{th}$ level node *(n-1)* all the way to the 1^{st} level node *a* connecting source i in plant p to any other sink j' in plant p''($M_{ip,j'p''}^{a,b,c,..,n-1,n}$).

$$M_{ip,jp\prime}^{a,b,c,..,n-1,n} = M_{ip,j\prime p\prime\prime}^{a,b,c,..,n-1,n}\ \forall i \in SU_p;\ \forall (j,j') \in SN_p;\ \forall (p,p',p'') \in P; \forall a \in X_{ip,jp'};\ \forall b \in Y_{ip,jp'}; \forall c \in Z_{ip,jp'} .. \forall (n-1) \in (N-1)_{ip,jp'}; \forall n \in N_{ip,jp'} \tag{100}$$

The flow from the freshwater mains to an n^{th} level node *n* through an $(n-1)^{th}$ level node *(n-1)* all the way to a 1^{st} level node *a* that eventually connects to sink j in plant p' ($F_{jp}^{a,b,c,..,n-1,n}$) must be equal to the flow associated with that n^{th} level node *n* through the same $(n-1)^{th}$ level node *(n-1)* all the way to the 1^{st} level node *a* connecting the freshwater mains to any other sink j' in plant p'($F_{j\prime,p\prime}^{a,b,c,..,n-1,n}$).

$$F_{jp}^{a,b,c,..,n-1,n} = F_{j\prime,p\prime}^{a,b,c,..,n-1,n}\ \forall (j,j') \in SN_p;\ \forall (p,p') \in P; \forall a \in X_{jp}; \forall b \in Y_{jp}; \forall c \in Z_{jp} .. \forall (n-1) \in (N-1)_{jp}; \forall n \in N_{jp} \tag{101}$$

The total flows across all branches connecting a source i in plant p to sink j in plant p' must be equal to the individual sum of all flows across each of the branches that establish the connection:

$M_{ip,jp'}^{a} + M_{ip,jp'}^{a,b} + M_{ip,jp'}^{a,b,c} + \cdots + M_{ip,jp'}^{a,b,c,..,n-1} + M_{ip,jp'}^{a,b,c,..,n} = M_{ip,jp'}\ \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p,p' \in P; \forall a \in X_{ip,jp'}\ ; \forall b \in Y_{ip,jp'}\ ; \forall c \in Z_{ip,jp'} .. \forall (n-1) \in (N-1)_{ip,jp'}; \forall n \in N_{ip,jp'}$ (102)

Similarly, the total flows across all branches connecting the freshwater mains to sink j in plant p' must be equal to the individual sum of all flows across each of the branches that establish the connection:

$F_{jp}^{a} + F_{jp}^{a,b} + M_{jp}^{a,b,c} + \cdots + F_{jp}^{a,b,c,..,n-1} + F_{jp}^{a,b,c,..,n} = F_{jp}\ \forall j \in SN_p;\ \forall p \in P; \forall a \in X_{jp}\ ; \forall b \in Y_{jp}\ ; \forall c \in Z_{jp} .. \forall (n-1) \in (N-1)_{jp}; \forall n \in N_{jp}$ (103)

Non-negative constraints are required for flows across any branch associated with establishing a connection from source i plant p to sink j plant p'

$M_{ip,jp'}^{a} \geq 0\ \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p,p' \in P; \forall a \in X_{ip,jp'}$ (104)

$M_{ip,jp'}^{a,b} \geq 0\ \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p,p' \in P; \forall a \in X_{ip,jp'}; \forall b \in Y_{ip,jp'}$ (105)

$M_{ip,jp'}^{a,b,c} \geq 0\ \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p,p' \in P; \forall a \in X_{ip,jp'}; \forall b \in Y_{ip,jp'}\ ; \forall c \in Z_{ip,jp'}$

(106)

$M_{ip,jp'}^{a,b,c,..,n} \geq 0\ \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p,p' \in P; \forall a \in X_{ip,jp'}; \forall b \in Y_{ip,jp'}\ ; \forall c \in Z_{ip,jp'} .. \forall n \in N_{ip,jp'}$

(107)

Similarly, non-negative constraints are required for flows across any branch associated with establishing a connection from the freshwater mains to sink j plant p'

$F_{jp}^{a} \geq 0\ \forall j \in SN_p;\ \forall p \in P; \forall a \in X_{jp}$ (108)

$F_{jp}^{a,b} \geq 0 \ \forall j \in SN_p;\ \forall p \in P; \forall a \in X_{jp}; \forall b \in Y_{jp}$ (109)

$F_{jp}^{a,b,c} \geq 0 \ \forall j \in SN_p;\ \forall p \in P; \forall a \in X_{jp}; \forall b \in Y_{jp}\ ; \forall c \in Z_{jp}$ (110)

$F_{jp}^{a,b,c,..,n} \geq 0 \ \forall j \in SN_p;\ \forall p \in P; \forall a \in X_{jp}; \forall b \in Y_{jp}\ ; \forall c \in Z_{jp}..\forall n \in N_{jp}$ (111)

IV.4.2 Backward Branching Formulation

Equations (112)-(136) below detail the mathematical formulation associated with a backward branching scheme in a pipeline.

The flow allocated to sink j in plant p' from source i in plant p ($M_{ip,jp'}$) must equal the summation of all flows ($M_{ip,jp'}^{a}$) from the various branches that connects sink j in plant p' to all 1st level nodes a, associated with the stream connection.

$\sum_{a=1}^{X_{ip,jp'}} M_{ip,jp'}^{a} = M_{ip,jp'} \quad \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p, p' \in P$ (112)

The flow allocated to wastewater mains from source i in plant p (D_{ip})must equal the summation of all flows $\left(D_{ip}^{a}\right)$from the various branches that connect the waste mains to all 1st level nodes a, associated with the stream connection.

$\sum_{a=1}^{X_{ip}} D_{ip}^{a} = D_{ip} \quad \forall i \in SU_p;\ \forall p \in P$ (113)

The flows allocated from each of the 1st level nodes in the stream that connects sink j in plant p' and source i in plant p ($M_{ip,jp'}^{a}$) must equal the summation of all flows ($M_{ip,jp'}^{a,b}$) from the various branches that connect each 1st level node a, to all 2nd level nodes *b* associated with the stream connection.

$$\sum_{b=1}^{Y_{ip,jp'}} M_{ip,jp'}^{a,b} = M_{ip,jp'}^{a} \quad \forall a \in X_{ip,jp'}; \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p, p' \in P \tag{114}$$

The flows allocated from each of the 1st level nodes in the stream that connects the wastewater mains and source i in plant p (D_{ip}^{a})must equal the summation of all flows $\left(D_{ip}^{a,b}\right)$ from the various branches that connect each 1st level node *a,* to all 2nd level nodes *b* associated with the stream connection.

$$\sum_{b=1}^{Y_{ip}} D_{ip}^{a,b} = D_{ip}^{a} \quad \forall a \in X_{ip}; \forall i \in SU_p;\ \forall p \in P \tag{115}$$

The flows allocated from each of the 2nd level nodes in the stream that connects sink j in plant p' and source i in plant p ($M_{ip,jp'}^{a,b}$) must equal the summation of all flows ($M_{ip,jp'}^{a,b,c}$) from the various branches that connect each 2nd level node *b,* to all 3rd level nodes *c* associated with the stream connection.

$$\sum_{c=1}^{Z_{ip,jp'}} M_{ip,jp'}^{a,b,c} = M_{ip,jp'}^{a,b} \quad \forall a \in X_{ip,jp'}; \forall b \in Y_{ip,jp'}; \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p, p' \in P \tag{116}$$

The flows allocated from each of the 2nd level nodes in the stream that connects the wastewater mains and source i in plant p ($D_{ip}^{a,b}$)must equal the summation of all flows $\left(D_{ip}^{a,b,c}\right)$ from the various branches that connect each 2nd level node *b,* to all 3rd level nodes *c* associated with the stream connection.

$$\sum_{c=1}^{Z_{ip}} D_{ip}^{a,b,c} = D_{ip}^{a,b} \quad \forall a \in X_{ip}; \forall b \in Y_{ip}; \forall i \in SU_p;\ \forall p \in P \tag{117}$$

The flows allocated from each of the (n-1)th level nodes in the stream that connects sink j in plant p' and source i in plant p ($M_{ip,jp'}^{a,b,c,..,n-1}$) must equal the summation of all flows ($M_{ip,jp'}^{a,b,c,..,n-1,n}$) from the various branches that connect each (n-1)th level node, to all nth level nodes associated with the stream connection.

$$\sum_{n=1}^{N_{ip,jp'}} M_{ip,jp'}^{a,b,c,..,n-1,n} = M_{ip,jp'}^{a,b,c,..,n-1} \quad \forall a \in X_{ip,jp'}; \forall b \in Y_{ip,jp'}; \forall c \in Z_{ip,jp'} \,..\, \forall(n-1) \in (N-1)_{ip,jp'}; \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p, p' \in P \qquad (118)$$

The flows allocated from each of the (n-1)th level nodes in the stream that connects the wastewater mains and source i in plant p ($D_{ip}^{a,b,c,..,n-1}$)must equal the summation of all flows $\left(D_{ip}^{a,b,c,..,n-1,n}\right)$ from the various branches that connect each (n-1)th level node, to all nth level nodes associated with the stream connection.

$$\sum_{n=1}^{N_{ip}} D_{ip}^{a,b,c,..,n-1,n} = D_{ip}^{a,b,c,..,n-1} \quad \forall a \in X_{ip}; \forall b \in Y_{ip}; \forall c \in Z_{ip} \,..\, \forall(n-1) \in (N-1)_{ip}; \forall i \in SU_p;\ \forall p \in P \qquad (119)$$

The flow to sink j in plant p' from a 1st level node *a* that receives flow from source i in plant p ($M_{ip,jp'}^{a}$) must be equal to the flow associated with the same 1st level node *a* connecting any other source i' in plant p'' to the same sink j in plant p' ($M_{i'p'',j'p'}^{a}$).

$$M_{ip,jp'}^{a} = M_{i'p'',jp'}^{a}\ \forall(i,i') \in SU_p;\ \forall j \in SN_p;\ \forall(p,p',p'') \in P; \forall a \in X_{ip,jp'} \qquad (120)$$

The flow to the wastewater mains from a 1st level node a that receives flow from source i in plant p (D_{ip}^{a}) must be equal to the flow associated with the same 1st level node connecting any other source i' in plant p' to the waste mains ($D_{i',p'}^{a}$).

$$D_{ip}^{a} = D_{i',p'}^{a}\ \forall(i,i') \in SU_p;\ \forall(p,p') \in P; \forall a \in X_{ip} \qquad (121)$$

The flow to sink j in plant p' from a 2nd level node b that receives flow through a 1st level node a that eventually connects back to source i in plant p ($M_{ip,jp''}^{a,b}$) must be equal to the flow associated with that 2nd level node b through the same 1st level node a connecting any other source i' in plant p'' to the same sink j in plant p' ($M_{i'p'',j'p'}^{a,b}$).

$$M_{ip,jp'}^{a,b} = M_{i'p'',jp'}^{a,b}\ \forall(i,i') \in SU_p;\ \forall j \in SN_p;\ \forall(p,p',p'') \in P; \forall a \in X_{ip,jp'}; \forall b \in Y_{ip,jp'} \tag{122}$$

The flow to the wastewater mains from a 2nd level node b that receives flow through a 1st level node a that eventually connects back to source i in plant p ($D_{ip}^{a,b}$) must be equal to the flow associated with that 2nd level node b through the same 1st level node a connecting any other source i' in plant p' to the waste mains ($D_{i',p'}^{a,b}$).

$$D_{ip}^{a,b} = D_{i',p'}^{a,b}\ \forall(i,i') \in SU_p;\ \forall(p,p') \in P; \forall a \in X_{ip}; \forall b \in Y_{ip} \tag{123}$$

The flow to sink j in plant p' from a 3rd level node c that receives flow through a 2nd level node b and a 1st level node a that eventually connects back to source i in plant p ($M_{ip,jp''}^{a,b,c}$) must be equal to the flow associated with that 3rd level node c through the same 2nd level node b and 1st level node a connecting any other source i' in plant p'' to the same sink j in plant p' ($M_{i'p'',j'p'}^{a,b,c}$).

$$M_{ip,jp'}^{a,b,c} = M_{i'p'',jp'}^{a,b,c}\ \forall(i,i') \in SU_p;\ \forall j \in SN_p;\ \forall(p,p',p'') \in P; \forall a \in X_{ip,jp'}; \forall b \in Y_{ip,jp'}; \forall c \in Z_{ip,jp'} \tag{124}$$

The flow to the wastewater mains from a 3rd level node c that receives flow through a 2nd level node b and a 1st level node a that eventually connects back to source i in plant p ($D_{ip}^{a,b,c}$) must be equal to the flow associated with that 3rd level node c through the same 2nd level node *b* and 1st level node *a* connecting any other source i' in plant p' to the waste mains($D_{i',p'}^{a,b,c}$).

$$D_{ip}^{a,b,c} = D_{i',p'}^{a,b,c} \; \forall(i,i') \in SU_p;\; \forall(p,p') \in P; \forall a \in X_{ip}; \forall b \in Y_{ip}; \forall c \in Z_{ip} \tag{125}$$

The flow to sink j in plant p' from an nth level node *n* through an (n-1)th level node *(n-1)* all the way to a 1st level node *a* that eventually connects back to source i in plant p ($M_{ip,jp'}^{a,b,c,..,n-1,n},$) must be equal to the flow associated with that nth level node *n* through the same (n-1)th level node *(n-1)* all the way to the 1st level node *a* connecting any other source i' in plant p'' to the same sink j in plant p' ($M_{i'p'',j'p'}^{a,b,c,..,n-1,n}$).

$$M_{ip,jp'}^{a,b,c,..,n-1,n} = M_{i'p'',jp'}^{a,b,c,..,n-1,n} \; \forall(i,i') \in SU_p;\; \forall j \in SN_p;\; \forall(p,p',p'') \in P; \forall a \in X_{ip,jp'}; \forall b \in Y_{ip,jp'}; \forall c \in Z_{ip,jp'} .. \forall(n-1) \in (N-1)_{ip,jp'}; \forall n \in N_{ip,jp'} \tag{126}$$

The flow to the wastewater mains from an nth level node *n* through an (n-1)th level node *(n-1)* all the way to a 1st level node *a* that eventually connects back to source i in plant p ($D_{ip}^{a,b,c,..,n-1,n}$) must be equal to the flow associated with that nth level node *n* through the same (n-1)th level node *(n-1)* all the way to the 1st level node *a* connecting any other source i' in plant p' to the waste mains ($D_{i',p'}^{a,b,c,..,n-1,n}$).

$$D_{ip}^{a,b,c,..,n-1,n} = D_{i',p'}^{a,b,c,..,n-1,n} \; \forall(i,i') \in SU_p;\; \forall(p,p') \in P; \forall a \in X_{ip}; \forall b \in Y_{ip}; \forall c \in Z_{ip} .. \forall(n-1) \in (N-1)_{ip}; \forall n \in N_{ip} \tag{127}$$

The total flows across all branches connecting a source i in plant p to sink j in plant p’ must be equal to the individual sum of all flows across each of the branches that establish the connection:

$$M_{ip,jp'}^{a} + M_{ip,jp'}^{a,b} + M_{ip,jp'}^{a,b,c} + \cdots + M_{ip,jp'}^{a,b,c,..,n} = M_{ip,jp'}\ \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p,p' \in P; \forall a \in X_{ip,jp'}\ ; \forall b \in Y_{ip,jp'}\ ; \forall c \in Z_{ip,jp'} .. \forall n \in N_{ip,jp'} \quad (128)$$

Moreover, the total flows across all branches connecting a source i in plant p to the wastewater mains must be equal to the individual sum of all flows across each of the branches that establish the connection:

$$D_{ip}^{a} + D_{ip}^{a,b} + D_{ip}^{a,b,c} + \cdots + D_{ip}^{a,b,c,..,n} = D_{ip}\ \forall i \in SU_p;\ \forall p \in P; \forall a \in X_{ip}\ ; \forall b \in Y_{ip}\ ; \forall c \in Z_{ip} .. \forall n \in N_{ip} \quad (129)$$

Moreover, non-negative constraints are required for flows across any branch associated with establishing a connection from source i plant p to sink j plant p’

$$M_{ip,jp'}^{a} \geq 0\ \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p \in P; \forall a \in X_{ip,jp'} \quad (130)$$

$$M_{ip,jp'}^{a,b} \geq 0\ \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p \in P; \forall a \in X_{ip,jp'}; \forall b \in Y_{ip,jp'} \quad (131)$$

$$M_{ip,jp'}^{a,b,c} \geq 0\ \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p \in P; \forall a \in X_{ip,jp'}; \forall b \in Y_{ip,jp'}\ ; \forall c \in Z_{ip,jp'} \quad (56)$$

$$M_{ip,jp'}^{a,b,c,..,n} \geq 0 \forall i \in SU_p;\ \forall j \in SN_p;\ \forall p \in P; \forall a \in X_{ip,jp'}\ ; \forall b \in Y_{ip,jp'}\ ; \forall c \in Z_{ip,jp'} .. \forall n \in N_{ip,jp'} \quad (132)$$

Similarly, non-negative constraints are required for flows across any branch associated with establishing a connection from source i plant p to the wastewater mains.

$$D_{ip}^{a} \geq 0\ \forall i \in SU_p;\ \forall i \in SU_p;\ \forall p \in P; \forall a \in X_{ip} \quad (133)$$

$$D_{ip}^{a,b} \geq 0 \ \forall i \in SU_p;\ \forall i \in SU_p;\ \forall p \in P; \forall a \in X_{ip}; \forall b \in Y_{ip} \tag{134}$$

$$D_{ip}^{a,b,c} \geq 0 \ \forall i \in SU_p;\ \forall i \in SU_p;\ \forall p \in P; \forall a \in X_{ip}; \forall b \in Y_{ip}\ ; \forall c \in Z_{ip} \tag{135}$$

$$D_{ip}^{a,b,c,..,n} \geq 0 \ \forall i \in SU_p;\ \forall i \in SU_p;\ \forall p \in P; \forall a \in X_{ip}; \forall b \in Y_{ip}\ ; \forall c \in Z_{ip}.. \forall n \in N_{ip} \tag{136}$$

IV.4.3 Problem Implementation

Since all source-to-sink connectivity options can take on both forms of branching, two different NLP optimization problems were solved in this work: (a) applying the forward merging formulation for source-to-sink and fresh-to-source connectivity (Equations ((86)-(111)); and (b) applying the backward merging formulation for the source-to-sink and sink-to-waste connectivity (Equations (112)-(136)). Both problems were implemented using “what’sBest9.0.5.0” LINDO Global Solver for Microsoft Excel 2010 on a desktop PC (Intel® Core ™ i7-2620M, 2.7 GHz, 8.00 GB RAM, 64-bit Operating System).

IV.5. Case Study

In order to demonstrate the pipeline merging aspects that have been accounted for in interplant water network synthesis problems, an illustrative case study example has been carried out as an illustration. The case study is adopted from Alnouri et al. (2014a), which considers each source-sink connection to be a separate pipeline. We have solved the two different problem formulations separately so as to compare the differences between applying forward and backward branching for the source-to-sink connectivity. The aim of this case study is to illustrate that merged networks can outperform segregated networks and are therefore important to consider in optimal inter-plant water integration. It was observed that merged pipelines offer more attractive solutions in terms of overall network cost-efficiency when compared to solutions attained when utilizing a single pipeline for each allocation involved within the network.

Figure 26 shows the industrial city layout that has been considered, which consists of an arrangement of 6 different industrial facility entities, 6 water sources, and 6 water sinks distributed across the cluster of plants. The plot was assumed to have a total area of 64 km^2. A case study that involves the same arrangement of plants has been previously implemented using a separate pipeline for every water allocation achieved (Alnouri, Linke et al. 2014a). In this work, results from both the previous and current implementation will be compared, so as to identify the best performing scenarios in terms of pipeline assembling options. Two interchanging locations have been assumed for the freshwater supply and the wastewater discharge mains, as illustrated in Figure 7. This helps in examining the influence of altering their respective positions on the piping arrangements attained, as well as the overall networks costs achieved. For each of these two cases, both forward and backward branching scenarios are applied on all source-to-sink connectivity within the network. Two different scenarios of merged pipeline instances, for source-to-sink interplant water transmission were studied. Thus, a total of four different options have been considered for the case study: (a) Case 1- forward branching on all source-to-sink connectivity, with position 1 for the fresh mains and position 2 for the waste mains; (b) Case 2- forward branching on all source-to-sink connectivity, with position 2 for the fresh mains and position 1 for the waste mains; (c) Case 3- backward branching on all source-to-sink connectivity, with position 1 for the fresh mains and position 2 for the waste mains; and (d) Case 4-backward branching on all source-to-sink connectivity, with position 2 for the fresh mains and position 1 for the waste mains.

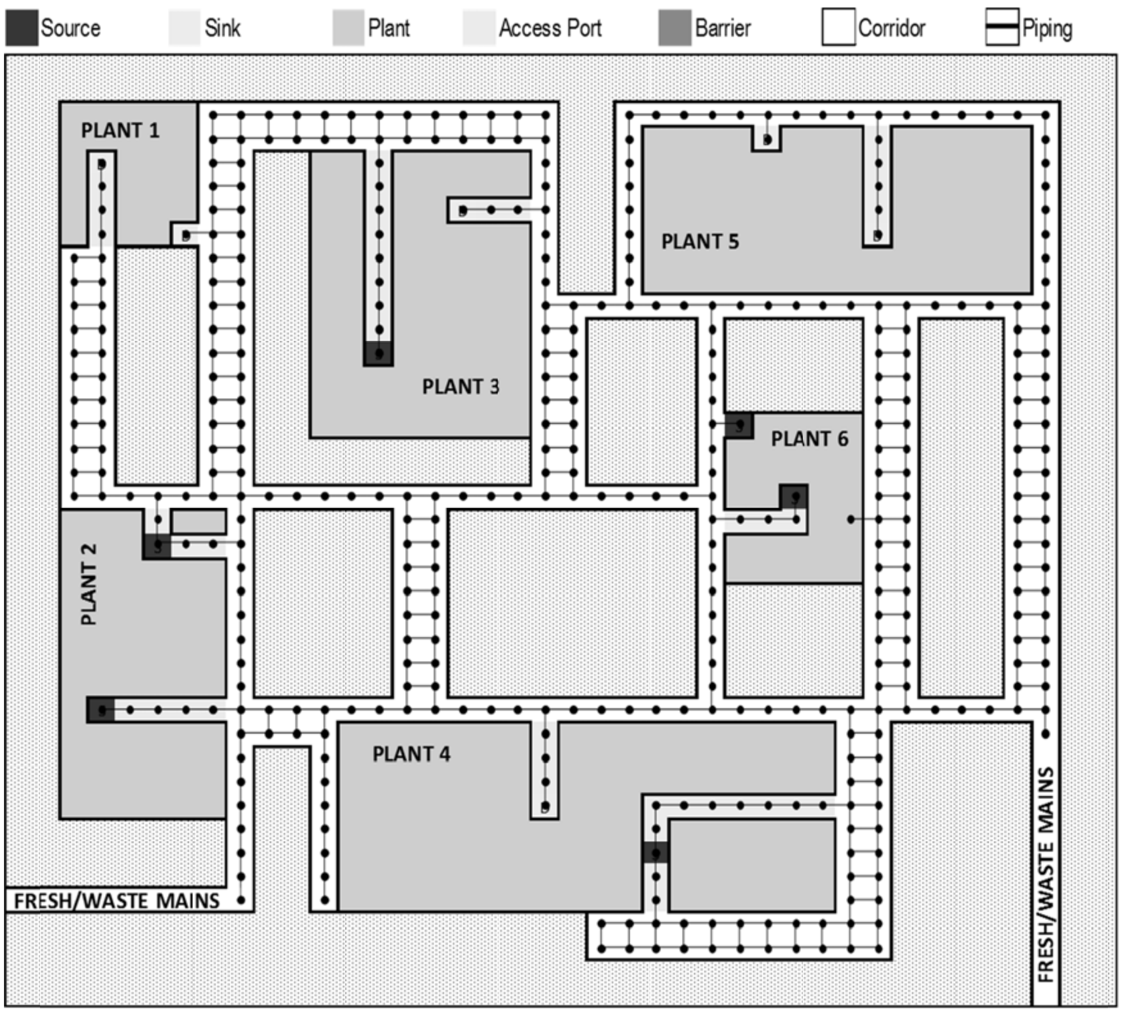

Figure 26. Industrial Zone arrangement for Case Study

Based on the explanation provided in the methodology section of this paper, it should be noted that only forward branching was implemented on the freshwater mains, and only backward branching was implemented for the wastewater mains in the various cases described above, even though both types of branching arrangements were investigated for source-to-sink connectivity involved.

Extracting the various optimum routing options, as well as the shortest path lengths associated with the respective pipeline branches was carried out using an analogous approach to the methodology that has been introduced in earlier work (Alnouri, Linke et al. 2014a). In this work, only Type 1 connectivity was employed for illustration purposes. Hence, a single connectivity mesh was developed for extracting optimum routing in right-angled pathways (Alnouri, Linke et al. 2014a). All cases were carried out using multiple contaminant information, whilst implementing all the four different settings that have been described above. Water source and sink flows, as well as source and sink contaminant information utilized in each of the different cases, are provided in Tables 35 and 36 respectively. Carbon steel Schedule 80 welded pipes, with cost parameters a=696.58 and b=1.215, were employed for all cases (Alnouri, Linke et al. 2014a). Moreover, a freshwater cost (C^{FRESH}) of 0.13 \$/ton was utilized, in addition to assuming 8760 hr/yr of operating hours (H_y). Additionally, all capital expenses were annualized using a constant factor (γ) = 0.05.

Table 35. Multiple Contaminant Source Data

Water Sources	Flow kg/h	Conc. X1 (ppm)	Conc. X2 (ppm)	Conc. X3 (ppm)
P2S2	120,000	100	50	30
P2S1	80,000	140	100	60
P3S1	140,000	180	150	130
P6S2	80,000	230	180	180
P6S1	195,000	250	190	200
P4S1	100,000	100	190	210

Table 36. Multiple Contaminant Sink Data

Water Sinks	Flow kg/h	Max. Inlet Conc. X1 (ppm)	Max. Inlet Conc. X2 (ppm)	Max. Inlet Conc. X3 (ppm)
P1D1	120,000	0	0	30
P1D2	80,000	50	50	80
P3D1	80,000	50	70	100
P5D1	140,000	140	100	100
P5D2	80,000	170	120	130
P4D1	195,000	240	130	150

When minimizing the total network costs for the different cases in terms of merged pipeline expenses as well as freshwater consumption, a total of 226.8t/h and 246.8t/h of minimum freshwater use and wastewater discharge were achieved respectively, for all the different scenarios that have been investigated (Cases 1-4). All source-sink mapping implementations that have been obtained were found to satisfy the same target values of minimum fresh and waste. Table 37 summarizes all optimized pipeline branch lengths using a forward branching scenario, as well as provides the values of the water flowrates associated with each branch, for Case 1. For that same case, Table 38 lists all the pipeline diameters that were obtained for each branch. Table 39 on the other hand summarizes all optimized pipeline branch lengths using a backward branching scenario (Case 3), as well as provides the values for all water flowrates associated with each branch.

Table 40 provides all the pipeline diameters that were obtained for each branch. According to the results obtained, interchanging the fresh and wastewater mains positions had no effect on the implementation obtained, neither on the diameters of the respective branches within the implementation. The only values changed were the optimized pipeline branch lengths associated with the fresh mains supplying water to the different sinks (i.e, the forward branching – Case 2), as well as the pipe branch lengths associated with waste mains receiving water from the various sources (i.e, the backward branching – Case 4).

Table 37. Optimized distances (km) and flows (t/h) associated with Forward Branching, using multiple contaminant information (Case 1)

	0.4	0	N	3.2	0	P1D1									
			N	2.8	0	P1D2									
			N	1.4	0	N	1.6	0	WASTE						
P2S1			N			N	3	0	P4D1						
	0.6	80	N			N	3	0	P3D2						
			N	2.6	80	N	4.8	80	N	0.2	32	P5D1			
			N			N			N	1.8	48	P5D2			
			N	1.6	0	WASTE									
			N	2.6	25.7	N	3	0	P1D1						
			N			N	1.8	25.71	P1D2						
P2S2	1	120	N			N	1.6	66.26	P4D1						
			N	1.4	94.2	N			N	3	14.28	P3D2			
			N			N	2.6	28.02	N	4.8	13.73	N	0.2	13.7	P5D1
			N			N			N			N	1.8	0	P5D2
			N			N	0.4	0	P1D2						
			N	1.8	0	N	2.2	0	N	3.8	0	P1D1			
			N			N			N	3.4	0	WASTE			
P3S1	1.8	140	N			N	0.6	0	P3D2						
			N	1.8	140	N			N	5.8	40.57	P4D1			
			N			N	0.8	140	N	3.2	99.42	N	0.2	67.42	P5D1
			N			N			N			N	1.8	32	P5D2
			N			N	3.6	0	N	3.6	0	P1D1			
			N	0.6	195	N			N	2.4	0	P1D2			
			N			N	3	195	N	3.8	186.8	WASTE			
P6S1	0.2	195	N			N			N	0.8	8.15	P4D1			
			N			N		0	P3D2						
			N	1.6	0	N	2.6	0	N	0.2	0	P5D1			
			N			N			N	1.8	0	P5D2			
			N			N			N	3	0	P3D2			
			N			N	1.2	0	N	2.4	0	N	2.4	0	P1D2
P6S2	0.8	80	N	0.2	0	N			N			N	3.6	0	P1D1
			N			N	4.8	0	N	0.2	0	P5D1			
			N			N			N	1.8	0	P5D2			
			N	2.8	80	N	0.8	80	P4D1						

Table 37. Continued

P6S2			N			N	3.8	0	WASTE									
			N	9.4	0	P5D2												
			N			N			N	0.8	0	P4D1						
			N			N	1.2	74.2	N			N	2.2	60	WASTE			
P4S1	1.8	100	N	1.8	100	N			N	1.6	74.28	N	2	14.28	N	4.2	0	P1D1
			N			N			N			N			N	4.2	14.28	P1D2
			N			N	1.8	25.71	N	4.2	25.71	P3D2						
			N			N			N	5	0	P5D1						
			N			N	6	40	P3D2									
			N			N			N	0.8	0	P4D1						
			N	2.4	200	N	1.2	160	N			N	2.2	0	WASTE			
FRESH	0.2	226.8421	N			N			N	1.6	160	N	2	160	N	4.2	120	P1D1
			N			N			N			N			N	3	40	P1D2
			N	6.2	26.84	N	1	26.84	P5D1									
			N			N	1	0	P5D2									

Table 38. Diameters (m) associated with Forward Branching, using multiple contaminant information (Case 1)

	0	0	N	0	0	P1D1						
			N	0	0	P1D2						
			N	0	0	N	0	0	WASTE			
P2S1			N			N	0	0	P4D1			
	0.16	0.2	N			N	0	0	P3D1			
			N	0.16	0.2	N	0.16	0.2	N	0.106	0.2	P5D1
			N			N			N	0.127	0.2	P5D2

Table 38. Continued

			N	0	0	WASTE									
			N	0.096	0.1	N	0	0	P1D1						
			N			N	0.096	0.1	P1D2						
P2S2	0.192	0.2	N	0.173	0.2	N	0.147	0.2	P4D1						
			N			N	0.101	0.2	N	0.074	0.1	P3D1			
			N			N			N	0.072	0.1	N	0.072	0.1	P5D1
			N			N			N			N	0	0	P5D2
			N	0	0	N	0	0	P1D2						
			N			N	0	0	N	0	0	P1D1			
			N			N			N	0	0	WASTE			
P3S1	0.206	0.3	N	0.206	0.3	N	0	0	P3D1						
			N			N	0.206	0.3	N	0.118	0.2	P4D1			
			N			N			N	0.177	0.2	N	0.148	0.2	P5D1
			N			N			N			N	0.106	0.2	P5D2
			N	0.239	0.3	N	0	0	N	0	0	P1D1			
			N			N			N	0	0	P1D2			
			N			N	0.231	0.3	N	0.235	0.3	WASTE			
P6S1	0.239	0.3	N			N			N	0.057	0.1	P4D1			
			N	0	0	N	0	0	P3D1						
			N			N	0	0	N	0	0	P5D1			
			N			N			N	0	0	P5D2			
			N	0	0	N	0	0	N	0	0	P3D1			
			N			N			N	0	0	N	0	0	P1D2
			N			N			N			N	0	0	P1D1
P6S2	0.16	0.2	N			N	0	0	N	0	0	P5D1			
			N			N			N	0	0	P5D2			
			N	0.16	0.2	N	0.16	0.2	P4D1						
			N			N	0	0	WASTE						

Table 38. Continued

			N	0	0	P5D2												
			N			N			N	0	0	P4D1						
			N			N	0.155	0.2	N			N	0.141	0.2	WASTE			
P4S1	0.177	0.2	N	0.177	0.2	N			N	0.155	0.2	N	0.074	0.1	N	0	0	P1D1
			N			N			N			N			N	0.074	0.1	P1D2
			N			N	0.0964	0.1	N	0.096	0.1	P3D1						
			N			N			N	0	0	P5D1						
			N			N	0.117	0.2	P3D1									
			N			N			N	0	0	P4D1						
			N	0.242	0.3	N	0.219	0.3	N			N	0	0	WASTE			
FRESH	0.256	0.3	N			N			N	0.219	0.3	N	0.219	0.3	N	0.192	0.2	P1D1
			N			N			N			N			N	0.117	0.2	P1D2
			N	0.098	0.1	N	0.098	0.1	P5D1									
			N			N	0	0	P5D2									

Table 39. Optimized distances (km) and flows (t/h) associated with Backward Branching, using multiple contaminant information (Case 3)

			N	0.4	0	P2S1												
			N			N	2.8	0	P2S2									
			N			N	5.8	0	P3S1									
P1D1	3.2	120	N	0.6	120	N			N	0.8	0	P6S1						
			N			N	3.4	120	N			N	0.8	0	P6S2			
			N			N			N	0.2	120	N	2.6	120	N	2.6	0	P4S1
			N			N			N			N			N	1.6	120	FRESH

Table 39. Continued

			N	0.6	0	P2S1															
			N			N	3.6	0	P3S1												
			N			N			N	2.8	25.71	P2S2									
P1D2	0.2	80	N	0.2	80	N			N			N	0.8	0	P6S1						
			N			N	2.2	80	N	3.4	54.28	N			N	0.8	0	P6S2			
			N			N			N			N	0.2	54.28	N	2.6	54.28	N	1.6	40	FR
			N			N			N			N			N			N	1.6	14.28	P4S1
			N	3.6	0	P3S1															
			N			N	2.4	14.28	N	2.4	0	P2S1									
			N			N			N	4.2	14.28	P2S2									
P3D1	0.6	80	N	0.8	80	N			N	6	40	FRESH									
			N			N	1.2	65.71	N			N	0.2	0	P6S1						
			N			N			N	1	25.71	N	0.8	25.71	N	0.8	0	P6S2			
			N			N			N			N			N	5.2	25.71	P4S1			
			N	9.4	40.57	P3S1															
			N			N	1.6	88.15	N	1	8.157	P6S1									
			N	1.2	88.15	N			N	0.8	80	P6S2									
P4D1	0.8	195	N			N	1	0	N	2.6	0	P4S1									
			N			N			N	1.6	0	FR									
			N	0.8	66.26	N	1.4	66.26	N	2	0	P2S1									
			N			N			N	1	66.26	P2S2									
			N	7.2	26.84	FRESH															
			N			N			N	4.6	67.42	P3S1									
			N			N	0.4	113.1	N	2.6	45.73	N	2.4	32	P2S1						
P5D1	0.2	140	N	2.6	113.1	N			N			N	4.2	13.73	P2S2						
			N			N			N	0.2	0	P6S1									
			N			N	1.6	0	N	0.8	0	N	0.8	0	P6S2						
			N			N			N			N	5.2	0	P4S1						
			N			N			N	4.6	32	P3S1									
			N			N	0.4	80	N	2.6	48	N	2.4	48	P2S1						
			N	3.4	80	N			N			N	4.2	0	P2S2						
P5D2	1	80	N			N	1.6	0	N	0.2	0	P6S1									
			N			N			N	1.6	0	P6S2									
			N	6.2	0	N	0.2	0	FR												
			N			N	4	0	P4S1												

Table 39. Continued

			N			N	1	0	P2S2			
			N	0.2	0	N	1.4	0	N	0.6	0	P2S1
			N			N			N	6.2	0	P3S1
WASTE	1.4	246.84	N			N	1.6	186.84	N	1	186.8	P6S1
			N	3.6	246.84	N			N	0.8	0	P6S2
			N			N	1	60	N	2.6	60	P4S1
			N			N			N	1.6	0	FRESH

Table 40. Diameters (m) associated with Backward Branching, using multiple contaminant information (Case 3)

			N	0	0	P2S1												
			N			N	0	0	P2S2									
			N			N	0	0	P3S1									
P1D1	0.192	0.2	N	0.192	0.2	N			N	0	0	P6S1						
			N			N	0.192	0.2	N			N	0	0	P6S2			
			N			N			N	0.192	0.2	N	0.192	0.2	N	0	0	P4S1
			N			N			N			N			N	0.192	0.2	FRESH
			N	0	0	P2S1												
			N			N	0	0	P3S1									
			N			N			N	0.096	0.1	P2S2						
P1D2	0.16	0.2	N	0.16	0.2	N			N			N	0	0	P6S1			
			N			N	0.16	0.2	N	0.134	0.2	N			N	0	0	P6S2
			N			N			N			N	0.134	0.2	N	0.134	0.2	N
			N			N			N			N			N			N
			N	0	0	P3S1												
			N			N	0.074	0.1	N	0	0	P2S1						
			N			N			N	0.074	0.1	P2S2						
P3D1	0.16	0.2	N	0.16	0.2	N			N	0.117	0.2	FRESH						
			N			N	0.147	0.2	N			N	0	0	P6S1			
			N			N			N	0.096	0.1	N	0.096	0.1	N	0	0	P6S2
			N			N			N			N			N	0.096	0.1	P4S1

Table 40. Continued

			N	0.118	0.2	P3S1									
			N	0.167	0.2	N	0.167	0.2	N	0.057	0.1	P6S1			
			N			N			N	0.16	0.2	P6S2			
P4D1	**0.239**	**0.3**	N			N	0	0	N	0	0	P4S1			
			N			N			N	0	0	FRESH			
			N	0.147	0.2	N	0.147	0.2	N	0	0	P2S1			
			N			N			N	0.147	0.2	P2S2			
			N	0.098	0.1	FRESH									
			N	0.187	0.2	N	0.187	0.2	N	0.148	0.2	P3S1			
			N			N			N	0.124	0.2	N	0.106	0.2	P2S1
P5D1	0.206	0.3	N			N			N			N	0.072	0.1	P2S2
			N			N	0	0	N	0	0	P6S1			
			N			N			N	0	0	N	0	0	P6S2
			N			N			N			N	0	0	P4S1
			N	0.16	0.2	N	0.16	0.2	N	0.106	0.2	P3S1			
			N			N			N	0.127	0.2	N	0.127	0.2	P2S1
			N			N			N			N	0	0	P2S2
P5D2	0.16	0.2	N			N	0	0	N	0	0	P6S1			
			N			N			N	0	0	P6S2			
			N	0	0	N	0	0	FRESH						
			N			N	0	0	P4S1						
			N			N	0	0	P2S2						
			N	0	0	N	0	0	N	0	0	P2S1			
WASTE	0.266	0.3	N			N			N	0	0	P3S1			
			N	0.266	0.3	N	0.235	0.3	N	0.235	0.3	P6S1			
			N			N			N	0	0	P6S2			
			N			N	0.141	0.2	N	0.141	0.2	P4S1			

Figures 27, 28, 29 and 30 provide illustrations of unmerged interplant network connectivity for Cases 1-4 respectively, utilizing the shortest routing options within the boundaries of the industrial city arrangement that has been provided.

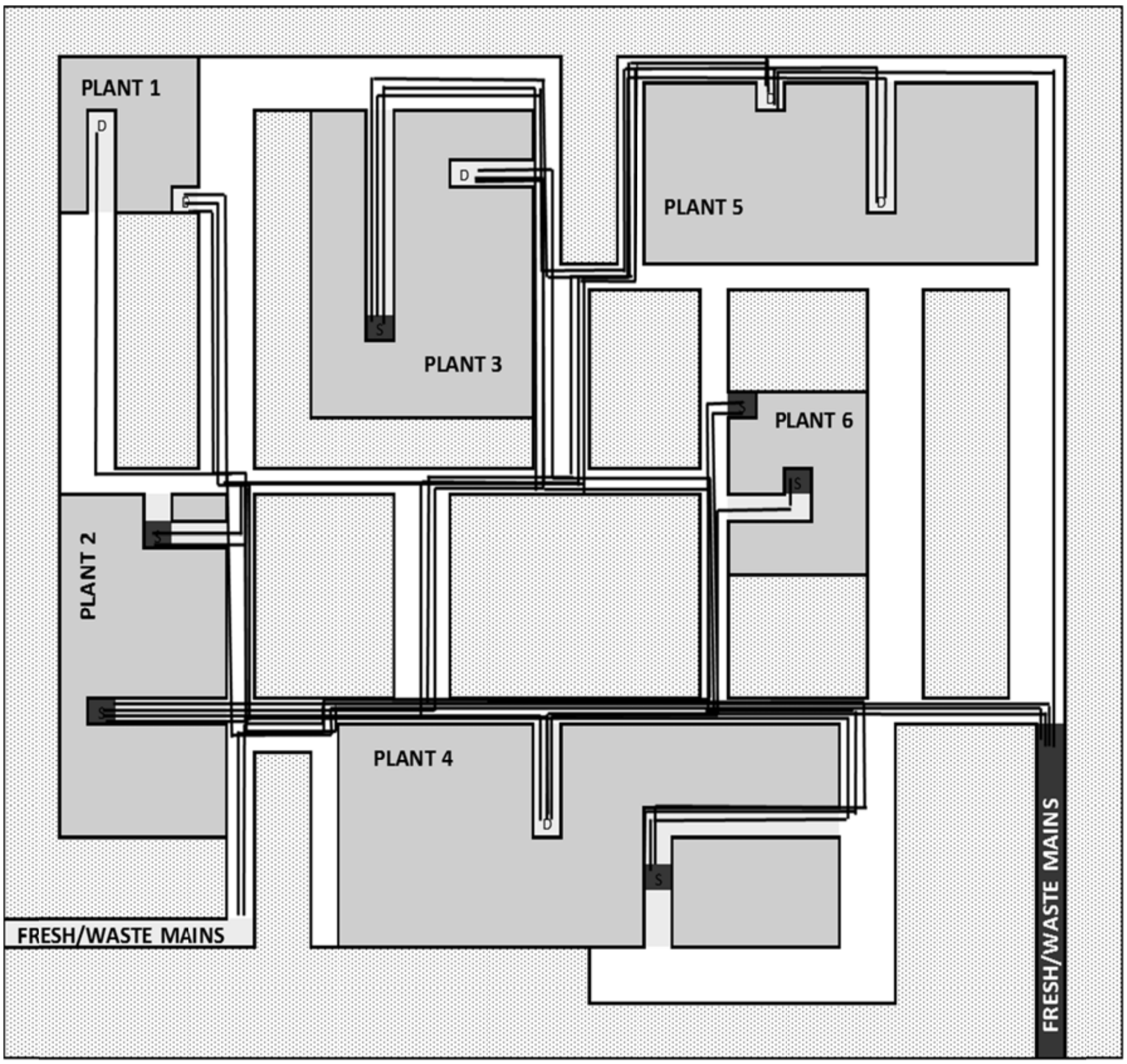

Figure 27. Case 1 unmerged interplant network solution illustrated

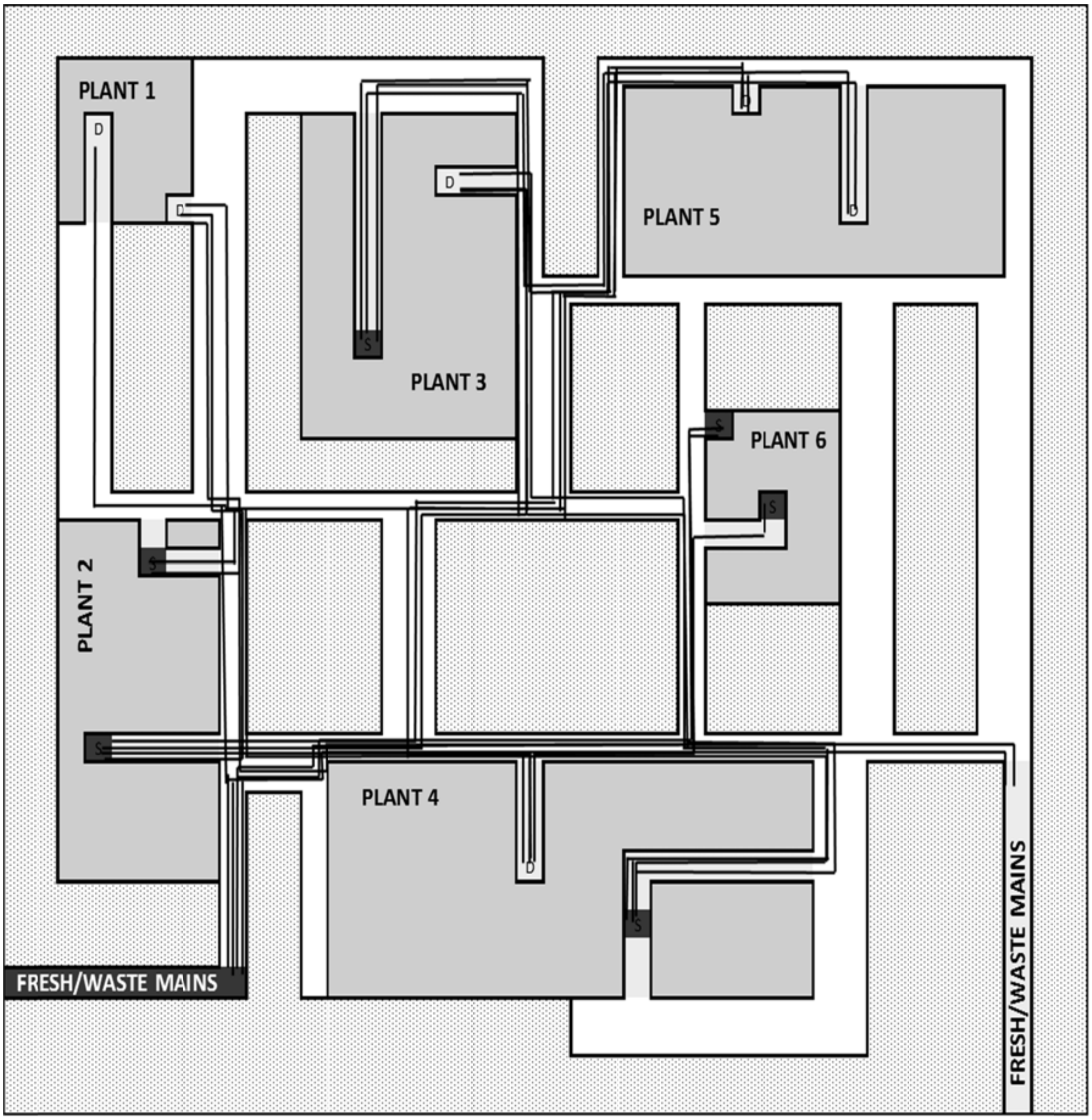

Figure 28. Case 2 unmerged interplant network solution illustrated

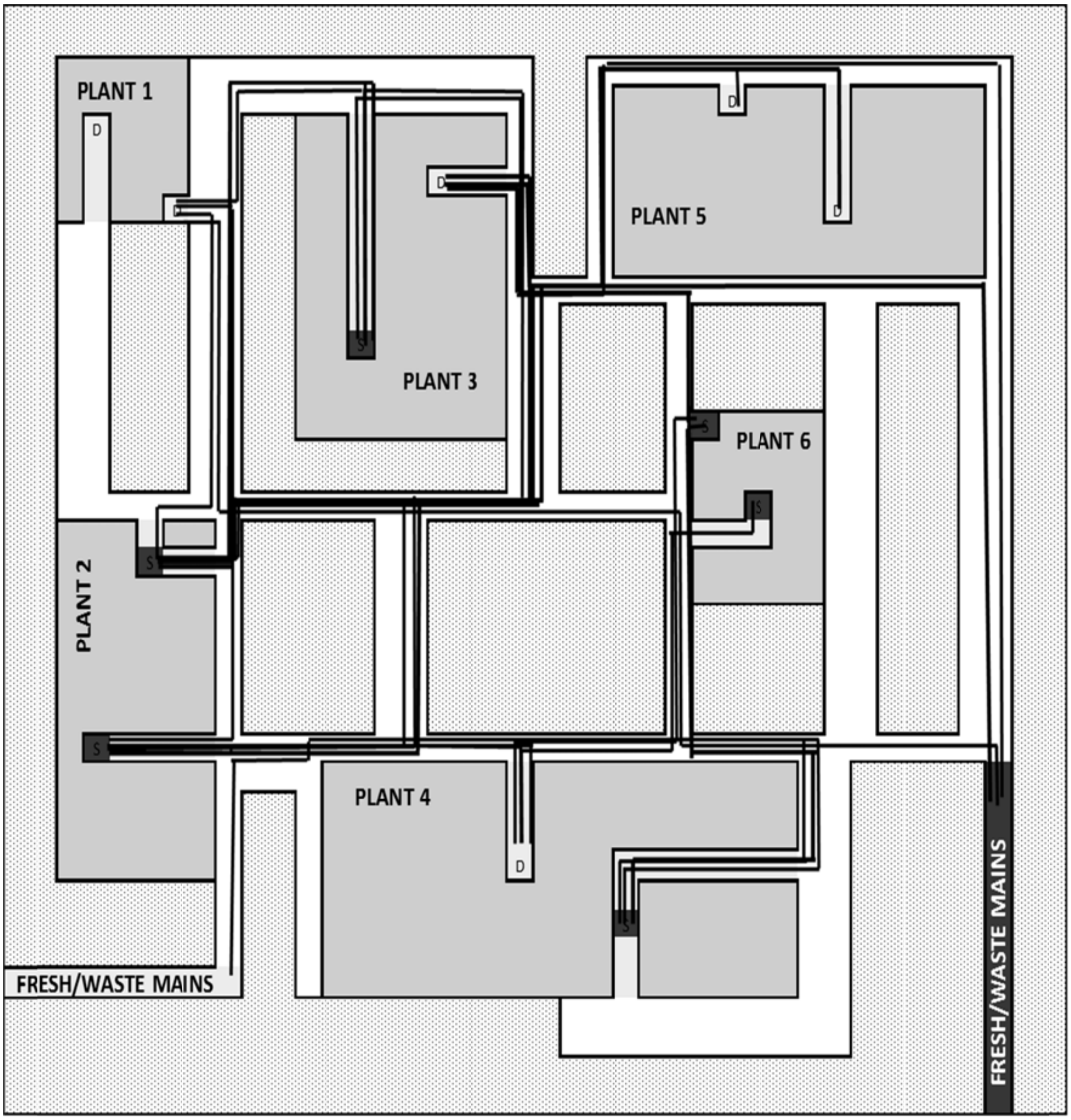

Figure 29. Case 3 unmerged interplant network solution illustrated

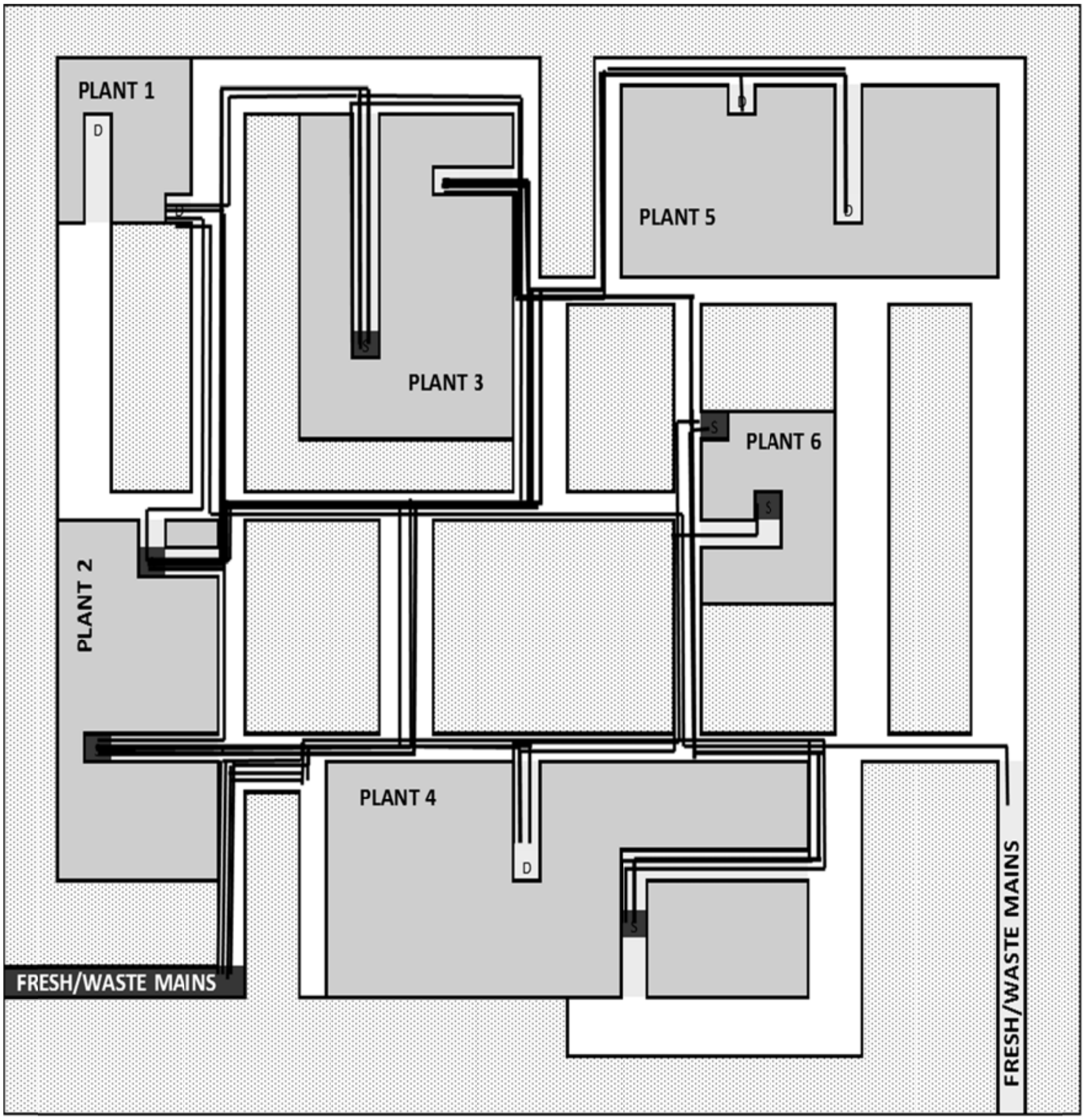

Figure 30. Case 4 unmerged interplant network solution illustrated

In all cases, many pipeline connections were attained in the optimal solution, thus indicating that it would be quite difficult to track and manage all pipeline transmission implementations attained. Figures 31, 32, 33 and 34 illustrate the corresponding merged pipeline solutions attained for the various interplant network designs. Figure 31 provides schematics of each optimal merged pipeline schematics via forward branching, for each given water source, distributing water to all sinks involved, whilst assuming position 1 for the fresh mains and position 2 for the waste mains. Figure 32 illustrates the different pipeline merging schematics via forward branching, when the fresh and waste mains positions are interchanged. It should be noted that the only single unmerged pipeline was associated with water source 2 in plant 6, transmitting water to sink 1 in plant 4, and hence was not shown in Figures 31 and 32. As mentioned earlier in this section, both forward and backward branching schemes, were investigated. Figure 33 illustrates the different pipeline merging schematics for all connections via backward branching, for each water sink, receiving water from all sources involved, whilst assuming position 1 for the fresh mains and position 2 for the waste mains. Similarly, Figure 34 illustrates the different pipeline merging schematics via backward branching, when the fresh and waste mains positions are interchanged. Similar to the forward branching cases, it should be noted that the only single unmerged pipeline was associated with freshwater being delivered to water source 1 in plant 1, and hence was not shown in Figures 33 and 34. Based on the solutions attained, it was evident that both forward and backward branching scenarios, the pipeline schematics do change according to the two different locations for the mains that have been assumed, as well as according to the branching scheme involved.

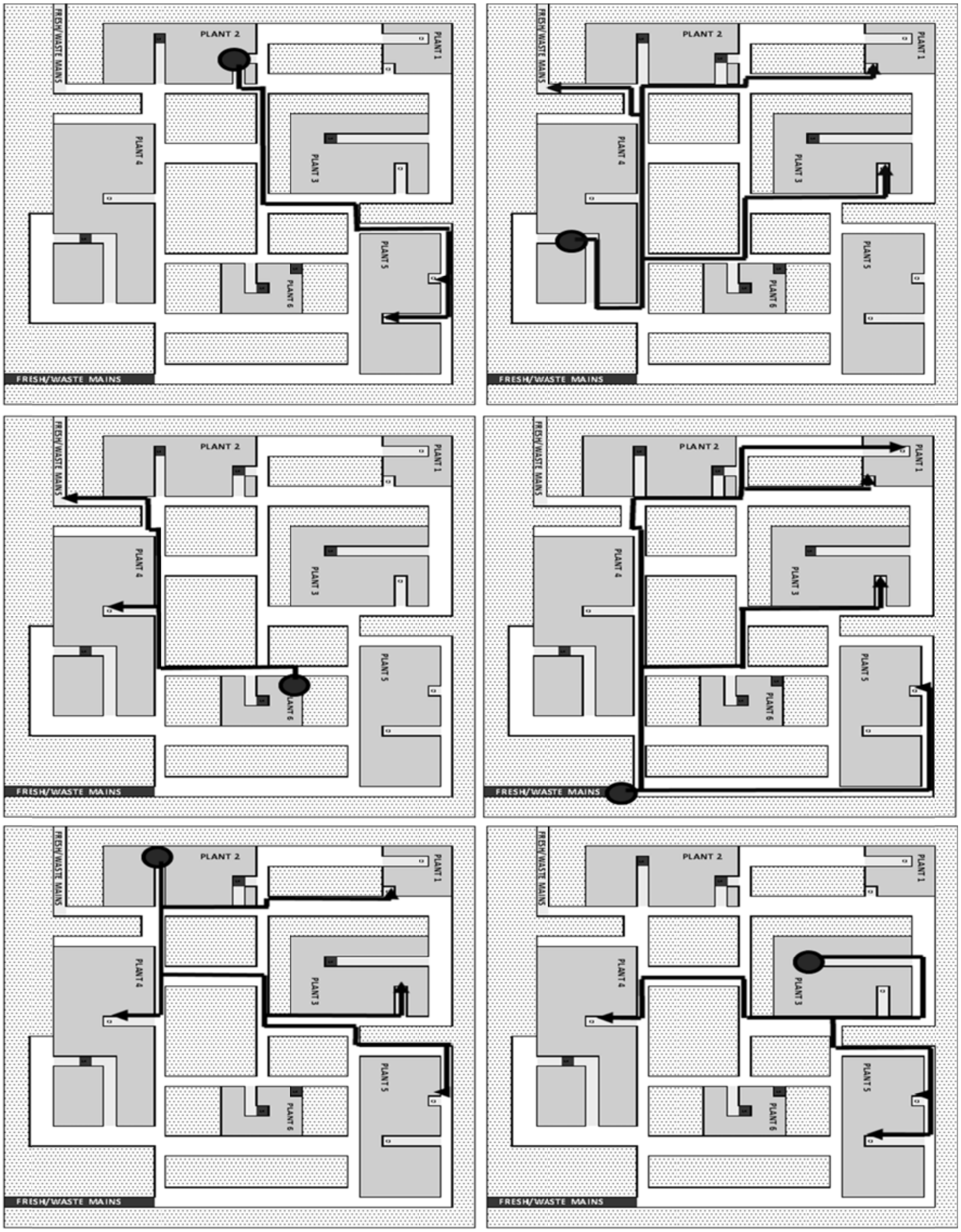

Figure 31. Case 1 interplant piping illustrated after merging, via forward branching

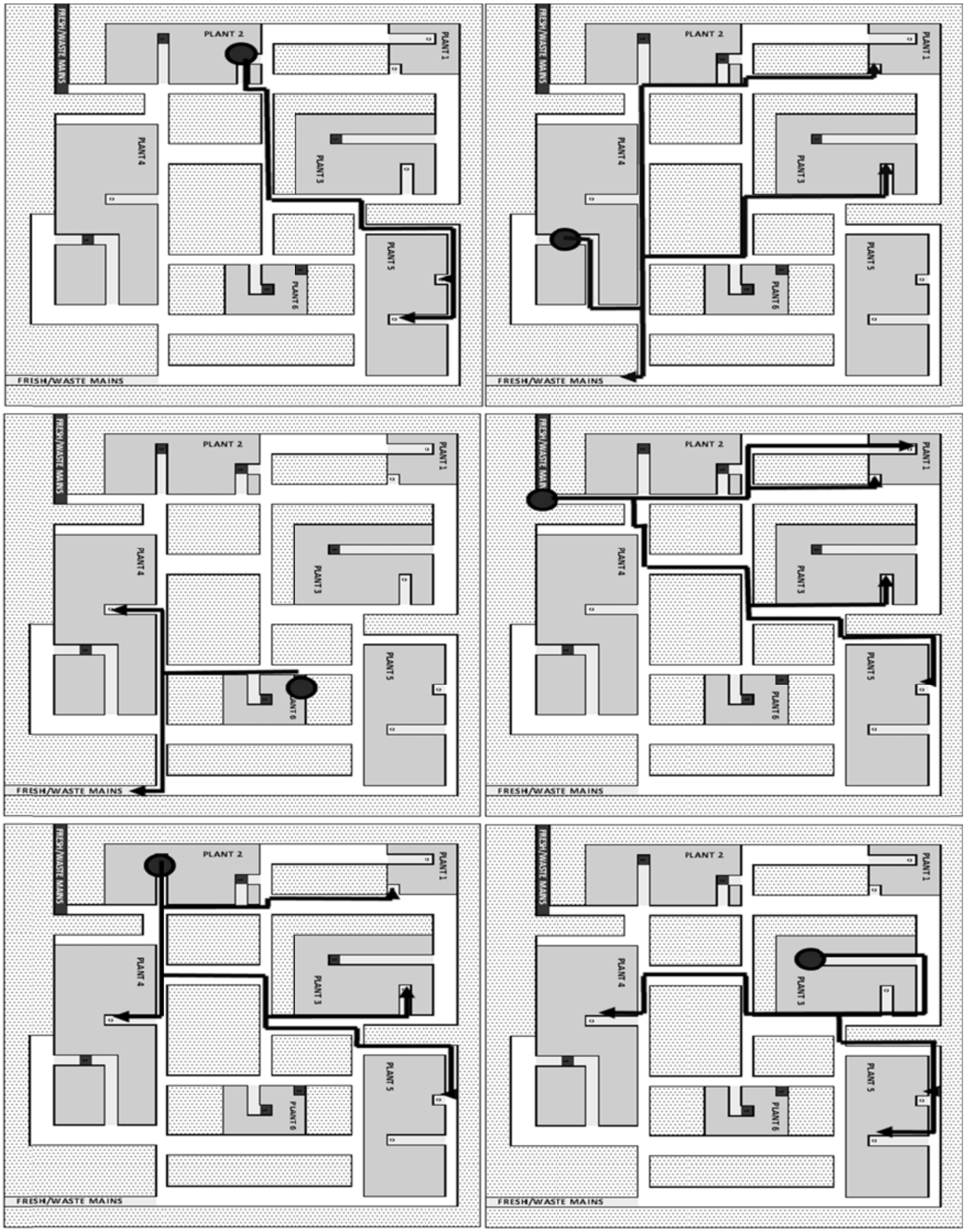

Figure 32. Case 2 interplant piping illustrated after merging, via forward branching

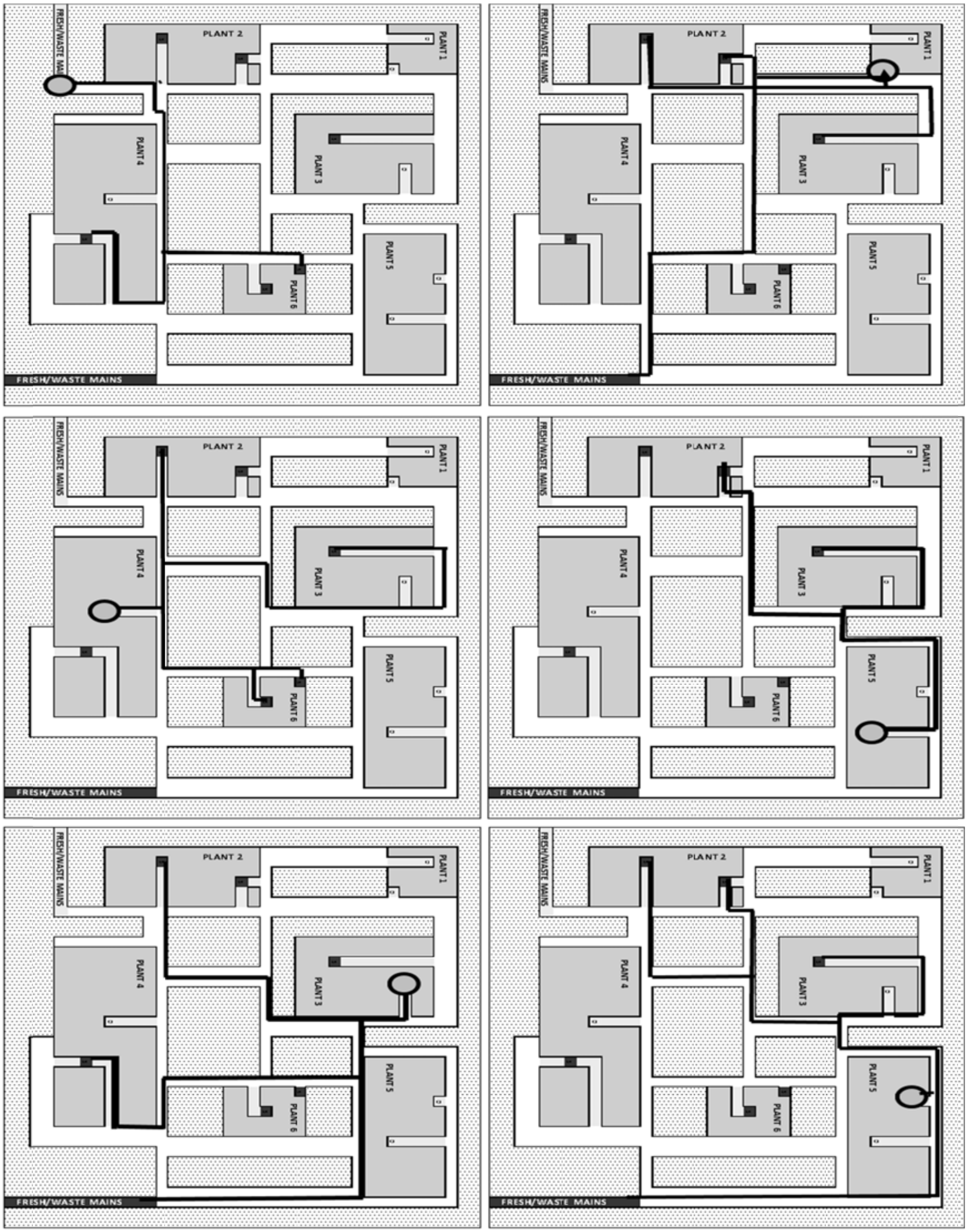

Figure 33. Case 3 interplant piping illustrated after merging, via backward branching

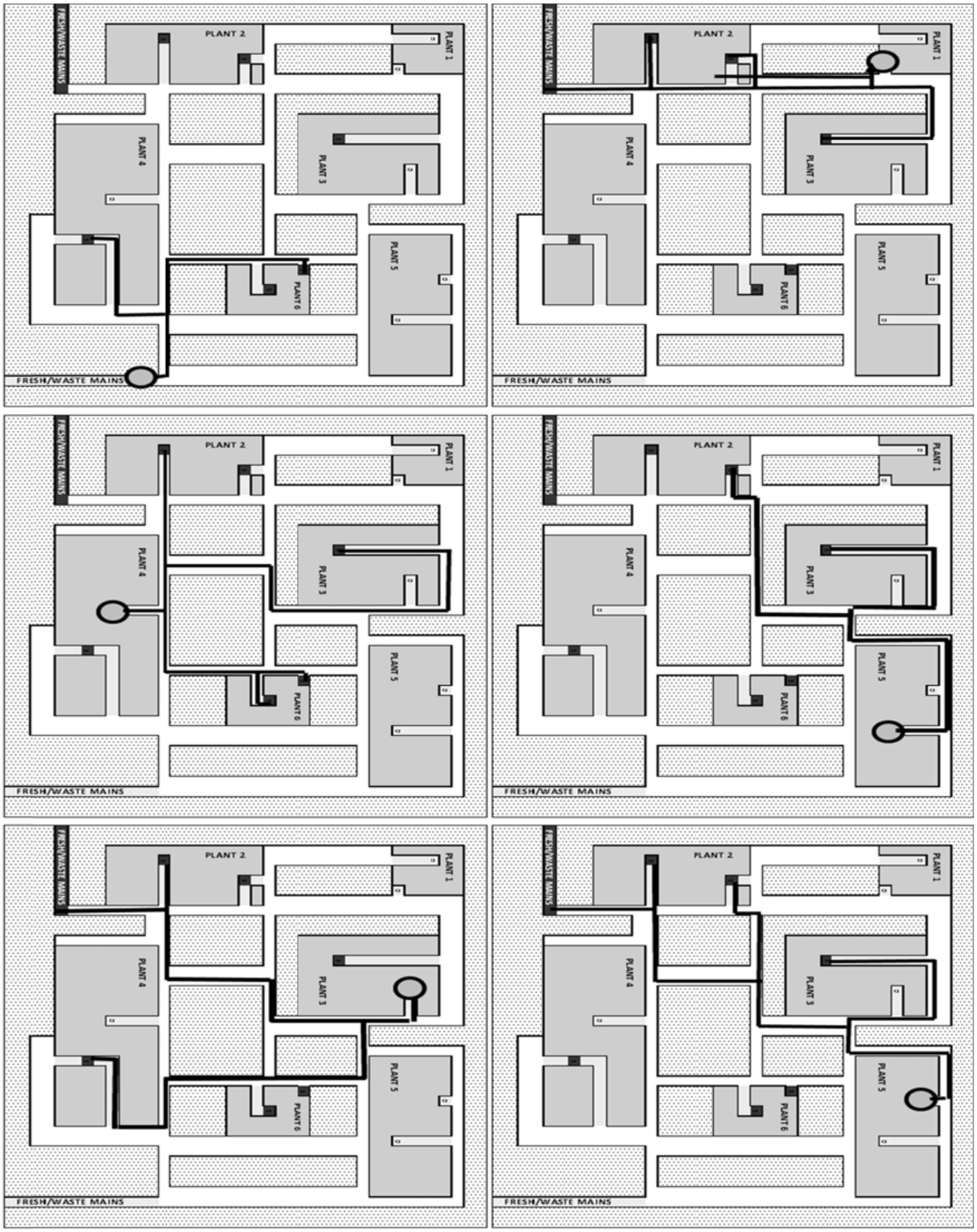

Figure 34. Case 4 interplant piping illustrated after merging, via backward branching

The respective network costs attained for the different scenarios that have been investigated are summarized in Table 41. The results indicate that forward branching was found to be more economical than backward branching in some cases, and vice versa, depending on the fresh and waste positions that have been assumed on the plot. For instance, forward branching was found to yield more cost effective solutions when compared to backward branching, assuming position 1 for the fresh mains and position 2 for the waste mains. On the other hand, when position 2 was assumed for the fresh mains and position 1 was assumed for the waste mains, backward pipeline branching gave more attractive solutions.

Table 41. Cost summary of all scenarios investigated with pipeline merging and a comparison of the network cost obtained before and after pipeline merging

Cost Item	Forward Branching Case 1	Forward Branching Case 2	Backward Branching Case 3	Backward Branching Case 4
Pipeline costs ($)	12,011,167	11,655,738	12,562,751	9,954,339
Total Fresh Costs ($/yr)	258,328	258,328	258,328	258,328
Annualized Piping + Fresh Costs ($/yr)	858,886	841,115	886,465	756,045
% Savings	-4.193% Savings	+2.713 (No savings)	-1.117% Savings	-7.675 Savings

The annualized piping costs that were obtained when no merging in between pipelines was implemented were all taken from previous work (Alnouri, Linke et al. 2014a), are had the following values: \$896,478/yr for the case assuming position 1 for the fresh mains and position 2 for the waste mains, that was compared with Cases 1 and 3 of this paper, and \$818,898/yr assuming position 2 for the fresh mains and position 4 for the waste mains, that was compared with Cases 2 and 4 of this paper. When assessed against the current results, after implementing the various pipeline merging scenarios that have been discussed, it was found that some of the merged cases do yield savings in terms of the piping costs obtained for the network. All savings were calculated accordingly, and provided in Table 41. It was observed that backward branching allowed for more savings in terms of network costs, compared to forward branching, with Case 4 being the highest in overall savings. Moreover, the results show that Case 2 incurs slight additional expenses after implementing pipeline merging schemes. This case resulted in no savings achieved, which was attributed to the fact that no extra flow was added to already existing pipeline diameters. The corresponding pipeline diameters utilized after merging had to be substantially increased, so as to accommodate for the combined water flowrate values to be transmitted and distributed within the network.

IV.6. Conclusions

Interplant water integration often entails the use of methodologies that could provide insight into how much freshwater consumption and wastewater discharge can be minimized to reach their respective targets, so as to allow for maximized water reuse amongst the various processing industries. This work investigates opportunities for carrying out interplant water network synthesis, whilst implementing pipeline merging arrangements within the designs, for water allocation, transmission and distribution amongst a given arrangement of plants within an industrial zone. For the purpose of attaining merged pipeline implementations, two different pipeline branching schemes were carried out in this work, forward branching, and backward branching. An illustrative case study has been carried out to demonstrate the proposed methodology, in which both different branching scenarios were investigated, using multiple contaminant information.

We have presented the first approach to address pipeline merging to water network synthesis. The main motivation has been to highlight that merged pipeline options can offer cost as well as complexity advantages over the standard assumption of segregated pipe connections between sources and sinks. The proposed scheme of pipe merging is not exhaustive and other merged pipeline options may exist that offer benefits. Future work will further develop the representation towards the inclusion of larger numbers of option.

For the two different formulations were adopted for the branching schemes, the type of branching utilized for all connections associated with each of the connectivity categories, i.e. (1) source-to-sink, (2) fresh-to-source, and (3) sink-to-waste, has been assumed to be the same in each case. As mentioned in the methodology discussion, connectivity categories (2) and (3) can only involve one of the branching types. However, source-to-sink connectivity has been allowed to incorporate a mix of both options. The case study illustrates the application of each branching scheme separately, and does not combine more than one merging choice for source-to-sink connectivity. However, there could be options in which a certain degree of mixing between forward and backward branching within the same connectivity category, that can outperform a single branching scheme solution. As a potential extension to this work, this aspect could be further investigated. Additionally, other merging options can be further investigated in terms of incorporating water quality specifications for interplant water transfer, which may be less efficient in terms of water use due to stream mixing, but could possibly lead to more efficient designs in terms of infrastructure cost.

CHAPTER V

PIPELINE MERGING CONSIDERATIONS FOR THE SYNTHESIS AND DESIGN OF INTERPLANT WATER NETWORKS WITH WASTEWATER TREATMENT, REGENERATION AND REUSE

The development of effective wastewater regeneration and reuse networks has been a prominent research focus, in response to the growing demand for freshwater use by the industrial sector. Moreover, many industrial cities are recognizing the benefits of reducing freshwater utilization, and wastewater discharge, by promoting effective wastewater treatment. Much of the research attention so far has primarily involved identifying optimal wastewater treatment and reuse strategies, in which several wastewater-producing operations are matched with a number of water-consuming operations, and/or assigned to undergo a series of treatment steps before reuse, if necessary. Moreover, a single pipeline is designated for every viable water allocation identified. This has been consistently observed in many of the previous research contributions that involve interplant water network synthesis. In an attempt to enhance the water network design process, several representations that account for a number of pipeline merging scenarios have been investigated for wastewater reuse networks. In addition to the improved design-screening ability of less complex pipeline networks, merging together common pipe segments that carry similar water qualities have been found to allow for various cost-enhancements in the designs obtained.

V.1. Introduction

Industrial water and wastewater management has become a crucial research priority in many regions, due to the immense scale of water-intensive industrial activities. Wastewater reuse certainly alleviates the depletion of available freshwater sources that are present around industrial areas. Moreover, many industrial sites that lie in proximity to coastal areas involve large volumes of unused wastewater being diverted back into the sea, which negatively impacts aquatic life (Englert, Zubrod et al. 2013). Hence, wastewater reuse also helps reduce the excessive wastewater quantities being discharged back into natural water bodies. Identifying appropriate wastewater treatment alternatives is considered of significant importance due to the stringent discharge limits being imposed on industrial wastewater, as well as the strict effluent standards that industries are expected to adhere to. Potential opportunities for industrial wastewater reuse (Ehrenfeld and Gertler, 1997) would absolutely vary from one industry to another, depending on the quantity and quality of wastewater produced.

The design of cost-effective wastewater regeneration and reuse networks has been the primary focus of many previous studies. For instance, Chew et al. (2008, 2009) developed a centralized hub topology for collecting, treating and redistributing water amongst groups of coexisting plants. Rubio-Castro et al. (2010, 2011) devised a MINLP optimization model for interplant water networks whilst incorporating environmental regulations for wastewater discharge. A problem reformulation that handles bilinear terms was also proposed. Biox et al. (2012) also studied water network design using a multi-objective optimization strategy. Later on, a structured representation has also been proposed, so as to capture the spatial aspects of water network design (Alnouri et al., 2014a). Effective planning of wastewater reuse networks have been captured with a focus on the following elements: (1) existing processing facilities, water consumption and wastewater production capacities, (2) site locations and the spatial distribution of all site entities that entail water use or production, and (3) common infrastructure boundaries, such as the existence of industrial corridors that can be utilized for water transportation. Subsequently, the spatial aspects of wastewater regeneration and reuse networks have also been studied (Alnouri, Linke et al. 2014b). Several different options for the selection of appropriate treatment technologies, as well as the efficient placement of corresponding treatment facilities, have been incorporated as follows: (1) a cluster of processing establishments sharing a common treatment facility (centralized), (2) the placement of a treatment facility as an individual entity belonging to a particular industrial site (decentralized). So far, most interplant water integration problems that have been studied associate every water allocation with a separate pipeline. In this work, a pipeline merging and assembling strategy for wastewater regeneration and reuse networks has been carried out.

V.2. Research Background

Exploring interplant water integration in terms of less complex and more economical options for the transmission and distribution of water in pipelines has been previously introduced for wastewater reuse networks (Alnouri et al., 2014c). In this work, efforts have been made to further improve the design process for wastewater reuse and regeneration networks. Most importantly, constructing interplant pipeline networks for water collection and transmission requires infrastructure availability, usually amongst a group of plants within geographic proximity. Moreover, the decision-making procedure involved with designing a cost-effective pipeline network for water transport can range from simple to complex. Various factors can greatly influence the design, such as the material choices available, as well as pipe construction and installation costs. Generally speaking, it is always considered more economical to employ a single-pipe transmission rather than multiple parallel pipes, especially when multiple locations are simultaneously involved. Hence, pipelines are usually constructed to accommodate a number of supply and destination points. Moreover, since pipeline systems are often made available in standard sizes, optimal diameter selection strategies for various pipe segments must also be incorporated, based on size availability.

V.3. Methodology and Problem Formulation

This work provides an extension to our work (Alnouri, Linke et al. 2014a) by incorporating options for the synthesis and design of merged pipeline networks involving wastewater treatment, regeneration, and reuse. In order to avoid unwanted water mixing in the merging procedure, the proposed methodology can be carried out on pipelines that carry treated, and untreated water qualities, individually. Hence, identifying cost-effective opportunities that allow the screening of less complex pipeline networks by assembling together commonly existing pipe sections, in the course of determining optimal water networks, have been based on the following two schemes:

V.3.1. Forward Branching Scheme

This pipeline branching approach corresponds to the transmission of water from a common location, to multiple nearby destinations. Hence, pipelines that apply a forward branching scheme is assembled by starting with one large pipe segment that combines all water in a given location to be distributed. The segments then narrows down to smaller ones that connect to multiple destinations. Forward branching can be applied to (1) source-to-sink and (2) fresh-to-source, and (3) source-to-treatment, (4) treatment-to-sink, and (5) treatment-to-waste connectivity categories. In addition to Equations (37)-(76) provided in Alnouri et al. (2010b), as well as Equations (86)-(111) provided in Alnouri et al. (2010c), Equations (137)-(162) below must also be utilized to devise the proposed forward branching scheme for the design of wastewater regeneration and reuse networks, and are described below.

The flow allocated from source i in plant p to decentralized treatment facility r in the same plant p $(T_{ip,rp})$ must equal the summation of all flows $\left(T_{ip,rp}^{a}\right)$ from the various branches that connect source i in plant p to all 1st level nodes a, associated with the stream connection.

$$\sum_{a=1}^{X_{ip,rp}} T_{ip,rp}^{a} = T_{ip,rp} \quad \forall i \in SU_p;\ \forall p \in P;\ \forall r \in R \tag{137}$$

The flow allocated from source i in plant p to centralized treatment facility s of type t ($T_{ip,st}$) must equal the summation of all flows $\left(T_{ip,st}^{a}\right)$ from the various branches that connect source i in plant p to all 1st level nodes a, associated with the stream connection.

$$\sum_{a=1}^{X_{ip,st}} T_{ip,st}^{a} = T_{ip,st} \quad \forall i \in SU_p;\ \forall p \in P;\ \forall s \in S;\ ;\ \forall t \in T \tag{138}$$

The flows allocated from each of the 1st level nodes in the stream that connects source i in plant p to decentralized treatment facility r in the same plant p ($T_{ip,rp}^{a}$) must equal the summation of all flows ($T_{ip,rp}^{a,b}$) from the various branches that connect each 1st level node a, to all 2nd level nodes b associated with the stream connection.

$$\sum_{b=1}^{Y_{ip,rp}} T_{ip,rp}^{a,b} = T_{ip,rp}^{a} \quad \forall a \in X_{ip,rp};\ \forall i \in SU_p;\ \forall p \in P;\ \forall r \in R \tag{139}$$

The flows allocated from each of the 1st level nodes in the stream that connects source i in plant p to centralized treatment facility s of type t ($T_{ip,st}^{a}$) must equal the summation of all flows ($T_{ip,st}^{a,b}$) from the various branches that connect each 1st level node a, to all 2nd level nodes b associated with the stream connection.

$$\sum_{b=1}^{Y_{ip,st}} T_{ip,st}^{a,b} = T_{ip,st}^{a} \quad \forall a \in X_{ip,st};\ \forall i \in SU_p;\ \forall p \in P;\ \forall s \in S;\ ;\ \forall t \in T \tag{140}$$

The flows allocated from each of the 2nd level nodes in the stream that c connects source i in plant p to decentralized treatment facility r in the same plant p ($T_{ip,rp}^{a,b}$) must equal the summation of all flows ($T_{ip,rp}^{a,b,c}$) from the various branches that connect each 2nd level node b, to all 3rd level nodes c associated with the stream connection.

$$\sum_{c=1}^{Z_{ip,rp}} T_{ip,rp}^{a,b,c} = T_{ip,rp}^{a,b}$$

$$\forall a \in X_{ip,rp};\ \forall b \in Y_{ip,rp};\ \forall i \in SU_p;\ \forall p \in P;\ \forall r \in R \qquad (141)$$

The flows allocated from each of the 2nd level nodes in the stream that connects source i in plant p to centralized treatment facility s of type t ($T_{ip,st}^{a,b}$) must equal the summation of all flows ($T_{ip,st}^{a,b,c}$) from the various branches that connect each 2nd level node *b*, to all 3rd level nodes *c* associated with the stream connection.

$$\sum_{c=1}^{Z_{ip,st}} T_{ip,st}^{a,b,c} = T_{ip,st}^{a,b}$$

$$\forall a \in X_{ip,st};\ \forall b \in Y_{ip,st};\ \forall i \in SU_p;\ \forall p \in P;\ \forall s \in S;\ ;\ \forall t \in T \qquad (142)$$

The flows allocated from each of the (n-1)th level nodes in the stream that connects source i in plant p to decentralized treatment facility r in the same plant p ($T_{ip,rp}^{a,b,c,..,n-1}$) must equal the summation of all flows ($T_{ip,rp}^{a,b,c,..,n-1,n}$) from the various branches that connect each (n-1)th level node, to all nth level nodes associated with the stream connection.

$$\sum_{n=1}^{N_{ip,rp}} T_{ip,rp}^{a,b,c,..,n-1,n} = T_{ip,rp}^{a,b,c,..,n-1} \quad \forall a \in X_{ip,rp};\ \forall b \in Y_{ip,rp};\ \forall c \in Z_{ip,rp} \,..\, \forall (n-1) \in (N-1)_{ip,rp}; \forall i \in SU_p;\ \forall p \in P;\ \forall r \in R \qquad (143)$$

The flows allocated from each of the (n-1)th level nodes in the stream that connects source i in plant p to centralized treatment facility s of type t ($T_{ip,rp}^{a,b,c,..,n-1}$) must equal the summation of all flows ($T_{ip,rp}^{a,b,c,..,n-1,n}$) from the various branches that connect each (n-1)th level node, to all nth level nodes associated with the stream connection.

$\sum_{n=1}^{N_{ip,st}} T_{ip,st}^{a,b,c,..,n-1,n} = T_{ip,st}^{a,b,c,..,n-1} \quad \forall a \in X_{ip,st};\ \forall b \in Y_{ip,st};\ \forall c \in Z_{ip,st} .. \forall (n-1) \in (N-1)_{ip,st};\ \forall i \in SU_p;\ \forall p \in P;\ \forall s \in S;\ ;\ \forall t \in T$ (144)

The flow from source i in plant p to a 1st level node a that eventually connects to a decentralized treatment facility r in the same plant p ($T_{ip,rp}^{a}$) must be equal to the flow associated with the same 1st level node a connecting source i in plant p to the same decentralized treatment facility r' in the same plant p ($T_{ip,r\prime p}^{a}$).

$T_{ip,rp}^{a} = T_{ip,r\prime p}^{a}\ \forall i \in SU_p; \forall p \in P; \forall (r, r') \in R;\ \forall a \in X_{ip,rp}$ (145)

The flow from source i in plant p to a 1st level node a that eventually connects to a centralized treatment facility s of type t ($T_{ip,st}^{a}$) must be equal to the flow associated with the same 1st level node a connecting source i in plant p to any other centralized treatment facility s' of type t' ($T_{ip,s\prime t\prime}^{a}$).

$T_{ip,st}^{a} = T_{ip,s\prime t\prime}^{a}\ \forall i \in SU_p; \forall p \in P; \forall (s, s') \in S;\ \forall (t, t') \in T;\ \forall a \in X_{ip,st}$ (146)

The flow from source i in plant p to a 2nd level node b through a 1st level node a that eventually connects to a decentralized treatment facility r in the same plant p ($T_{ip,rp}^{a,b}$) must be equal to the flow associated with that 2nd level node b through the same 1st level node a connecting source i in plant p to any other decentralized treatment facility r' in the same plant p ($T_{ip,r\prime p}^{a,b}$).

$T_{ip,rp}^{a,b} = T_{ip,r\prime p}^{a,b}, \forall i \in SU_p; \forall p \in P; \forall (r, r') \in R;\ \forall a \in X_{ip,rp}; \forall b \in Y_{ip,rp}$ (147)

The flow from source i in plant p to a 2nd level node *b* through a 1st level node *a* that eventually connects to a centralized treatment facility s of type t ($T_{ip,st}^{a,b}$) must be equal to the flow associated with that 2nd level node *b* through the same 1st level node *a* connecting source i in plant p to any other centralized treatment facility s' of type t'($T_{ip,s't'}^{a,b}$).

$$T_{ip,st}^{a,b} = T_{ip,s't'}^{a,b}\ \forall i \in SU_p; \forall p \in P; \forall (s,s') \in S;\ \forall (t,t') \in T;\ \forall a \in X_{ip,st}; \forall b \in Y_{ip,st} \tag{148}$$

The flow from source i in plant p to a 3rd level node *c* through a 2nd level node *b* and a 1st level node *a* that eventually connects to a decentralized treatment facility r in the same plant p ($T_{ip,rp}^{a,b,c}$) must be equal to the flow associated with that 3rd level node *c* through the same 2nd level node *b* and 1st level node *a* connecting source i in plant p to any other decentralized treatment facility r' in the same plant p ($T_{ip,r'p}^{a,b,c}$).

$$T_{ip,rp}^{a,b,c} = T_{ip,r'p}^{a,b,c}, \forall i \in SU_p; \forall p \in P; \forall (r,r') \in R;\ \forall a \in X_{ip,rp}; \forall b \in Y_{ip,rp}; \forall c \in Z_{ip,jp'} \tag{149}$$

The flow from source i in plant p to a 3rd level node *c* through a 2nd level node *b* and a 1st level node *a* that eventually connects to a centralized treatment facility s of type t ($T_{ip,st}^{a,b,c}$) must be equal to the flow associated with that 3rd level node *c* through the same 2nd level node *b* and 1st level node *a* connecting source i in plant p to any other centralized treatment facility s' of type t'($T_{ip,s't'}^{a,b,c}$).

$T_{ip,st}^{a,b,c} = T_{ip,s't'}^{a,b,c}\ \forall i \in SU_p; \forall p \in P; \forall (s,s') \in S;\ \forall (t,t') \in T;\ \forall a \in X_{ip,st}; \forall b \in Y_{ip,st}; \forall c \in Z_{ip,jp'}$ (150)

The flow from source i in plant p to an n^{th} level node *n* through an $(n\text{-}1)^{th}$ level node *(n-1)* all the way to a 1^{st} level node *a* that eventually connects to a decentralized treatment facility r in the same plant p ($T_{ip,rp}^{a,b,c,..,n-1,n}$) must be equal to the flow associated with that n^{th} level node *n* through the same $(n\text{-}1)^{th}$ level node *(n-1)* all the way to the 1^{st} level node *a* connecting source i in plant p to any other decentralized treatment facility r' in the same plant p ($T_{ip,r'p}^{a,b,c,..,n-1,n}$).

$T_{ip,rp}^{a,b,c,..,n} = T_{ip,r'p}^{a,b,c,..,n}, \forall i \in SU_p; \forall p \in P; \forall (r,r') \in R;\ \forall a \in X_{ip,rp}; \forall b \in Y_{ip,rp}; \forall c \in Z_{ip,rp} .. \forall (n-1) \in (N-1)_{ip,rp}; \forall n \in N_{ip,rp}$ (151)

The flow from source i in plant p to an n^{th} level node *n* through an $(n\text{-}1)^{th}$ level node *(n-1)* all the way to a 1^{st} level node *a* that eventually connects to a centralized treatment facility s of type t ($T_{ip,st}^{a,b,c,..,n-1,n}$) must be equal to the flow associated with that n^{th} level node *n* through the same $(n\text{-}1)^{th}$ level node *(n-1)* all the way to the 1^{st} level node *a* connecting source i in plant p to any other centralized treatment facility s' of type t'($T_{ip,s't'}^{a,b,c,..,n-1,n}$).

$T_{ip,st}^{a,b,c,..,n-1,n} = T_{ip,s't'}^{a,b,c,..,n-1,n}\ \forall i \in SU_p; \forall p \in P; \forall (s,s') \in S;\ \forall (t,t') \in T;\ \forall a \in X_{ip,st}; \forall b \in Y_{ip,st}; \forall c \in Z_{ip,st} .. \forall (n-1) \in (N-1)_{ip,st}; \forall n \in N_{ip,st}$ (152)

Additionally, the total flows across all branches connecting a source i in plant p to a de-central treatment facility r within the same plant p, or to a shared central treatment facility s of type t must be equal to the individual sum of all flows across each of the branches that establish the connection, respectively:

$$T_{ip,rp}^{a} + T_{ip,rp}^{a,b} + T_{ip,rp}^{a,b,c} + \cdots + T_{ip,rp}^{a,b,c,..,n-1} + T_{ip,rp}^{a,b,c,..,n} = T_{ip,rp} \ \forall i \in SU_p; \forall p \in P; \forall r \in R; \forall a \in X_{ip,rp}\ ; \forall b \in Y_{ip,rp}\ ; \forall c \in Z_{ip,rp} \ldots \forall (n-1) \in (N-1)_{ip,rt}; \forall n \in N_{ip,rt} \tag{153}$$

$$T_{ip,st}^{a} + T_{ip,st}^{a,b} + T_{ip,st}^{a,b,c} + \cdots + T_{ip,st}^{a,b,c,..,n-1} + T_{ip,st}^{a,b,c,..,n} = T_{ip,st} \ \forall i \in SU_p; \forall p \in P; \forall s \in S; \forall t \in T; \forall a \in X_{ip,st}\ ; \forall b \in Y_{ip,st}\ ; \forall c \in Z_{ip,st} .. \forall (n-1) \in (N-1)_{ip,st}; \forall n \in N_{ip,st} \tag{154}$$

Non-negative constraints are required for flows across any branch associated with establishing a connection from source i plant p to sink j plant p'
In addition, non-negative constraints must be maintained for all flows across any branch associated with establishing a connection from a source i in plant p to a de-central treatment facility r in the same plant p.

$$T_{ip,rp}^{a} \geq 0 \ \forall i \in SU_p; \forall p \in P; \forall r \in R; \forall a \in X_{ip,rp} \tag{155}$$

$$T_{ip,rp}^{a,b} \geq 0 \ \forall i \in SU_p; \forall p \in P; \forall r \in R; \forall a \in X_{ip,rp}; \forall b \in Y_{ip,rp} \tag{156}$$

$$T_{ip,rp}^{a,b,c} \geq 0 \ \forall i \in SU_p;\ \ \forall p \in P; \forall r \in R; \forall a \in X_{ip,jp'}; \forall b \in Y_{ip,rp}\ ; \forall c \in Z_{ip,rp} \tag{157}$$

…

$T_{ip,rp}^{a,b,c,..,n} \geq 0\ \forall i \in SU_p;\ \forall p \in P; \forall r \in R; \forall a \in X_{ip,rp}\ ; \forall b \in Y_{ip,rp}\ ; \forall c \in Z_{ip,rp} .. \forall n \in N_{ip,rp}$ (158)

Similarly, non-negative constraints must be maintained for all flows across any branch associated with establishing a connection from a source i in plant p to a central treatment facility s of type t.

$T_{ip,st}^{a} \geq 0\ \forall i \in SU_p;\ \forall p \in P; \forall s \in S; \forall t \in T; \forall a \in X_{ip,st}$ (159)

$T_{ip,st}^{a,b} \geq 0\ \forall i \in SU_p;\ \forall p \in P; \forall s \in S; \forall t \in T; \forall a \in X_{ip,st}; \forall b \in Y_{ip,st}$ (160)

$T_{ip,st}^{a,b,c} \geq 0\ \forall i \in SU_p;\ \forall p \in P; \forall s \in S; \forall t \in T; \forall a \in X_{ip,st}; \forall b \in Y_{ip,st}\ ; \forall c \in Z_{ip,st}$

(161)

…

$T_{ip,st}^{a,b,c,..,n} \geq 0\ \forall i \in SU_p;\ \forall p \in P; \forall s \in S; \forall t \in T; \forall a \in X_{ip,st}\ ; \forall b \in Y_{ip,st}\ ; \forall c \in Z_{ip,st} .. \forall n \in N_{ip,st}$ (162)

V.3.2. Backward Branching Scheme

This pipeline branching approach corresponds to the transmission of water from a number of nearby locations, to a single destination. Hence, pipelines that apply a backward branching scheme is assembled by starting with multiple small pipe segment that connect to a single location. The segments widen up and combine as the destination is approached. Backward branching can be applied to (1) source-to-sink and (2) sink-to-waste, (4) treatment-to-sink, and (5) treatment-to-waste connectivity categories. Similar to the forward branching scenario case, Equations (163)-(214) described below must also be utilized to devise the proposed backward branching scheme for the design of wastewater regeneration and reuse networks, in addition to Equations (37)-(76) provided in Alnouri et al. (2010b), as well as equations (112)-(136) provided in in Alnouri et al. (2010c).

The flow allocated to sink j in plant p' from decentralized treatment facility r in plant p $(T_{rp,jp'})$ must equal the summation of all flows $\left(T_{rp,jp'}^{a}\right)$ from the various branches that connect sink j in plant p' to all 1st level nodes a, associated with the stream connection.

$$\sum_{a=1}^{X_{rp,jp'}} T_{rp,jp'}^{a} = T_{rp,jp'} \quad \forall j \in SN_p;\ \forall p, p' \in P;\ \forall r \in R \tag{163}$$

The flow allocated to sink j in plant p' from centralized treatment facility s of type t $(T_{st,jp})$ must equal the summation of all flows $\left(T_{st,jp}^{a}\right)$ from the various branches that connect sink j in plant p' to all 1st level nodes a, associated with the stream connection.

$$\sum_{a=1}^{X_{st,jp}} T_{st,jp}^{a} = T_{st,jp} \quad \forall j \in SN_p;\ \forall p \in P;\ \forall s \in S;\ \forall t \in T \tag{164}$$

The flow allocated to wastewater mains from decentralized treatment facility r in plant p (D_{rp}) must equal the summation of all flows $\left(D_{rp}^{a}\right)$from the various branches that connect the waste mains to all 1st level nodes a, associated with the stream connection.

$$\sum_{a=1}^{X_{rp}} D_{rp}^{a} = D_{rp} \quad \forall r \in R;\ \forall p \in P \tag{165}$$

The flow allocated to wastewater mains from centralized treatment facility s of type t (D_{st}) must equal the summation of all flows (D_{st}^{a}) from the various branches that connect the waste mains to the 1st level nodes a, associated with the stream connection.

$$\sum_{a=1}^{X_{st}} D_{st}^{a} = D_{st} \quad \forall s \in S;\ \forall t \in T \tag{166}$$

The flows allocated from each of the 1st level nodes in the stream that connects sink j in plant p' and decentralized treatment facility r in plant p ($T_{rp,jp'}^{a}$) must equal the summation of all flows $\left(T_{rp,jp'}^{a,b}\right)$ from the various branches that connect each 1st level node a, to all 2nd level nodes b associated with the stream connection.

$$\sum_{b=1}^{Y_{rp,jp'}} T_{rp,jp'}^{a,b} = T_{rp,jp'}^{a} \quad \forall a \in X_{rp,jp'}; \forall j \in SN_p;\ \forall p, p' \in P;\ \forall r \in R \tag{167}$$

The flows allocated from each of the 1st level nodes in the stream that connects sink j in plant p' and centralized treatment facility s of type t ($T_{st,jp}^{a}$) must equal the summation of all flows $\left(T_{st,jp}^{a,b}\right)$ from the various branches that connect each 1st level node a, to all 2nd level nodes b associated with the stream connection.

$$\sum_{b=1}^{Y_{st,jp}} T_{st,jp}^{a,b} = T_{st,jp}^{a} \quad \forall a \in X_{st,jp}; \forall j \in SN_p;\ \forall p \in P;\ \forall s \in S;\ \forall t \in T \tag{168}$$

The flows allocated from each of the 1st level nodes in the stream that connects the wastewater mains and decentralized treatment facility r in plant p (D_{rp}^{a}) must equal the summation of all flows $\left(D_{rp}^{a,b}\right)$ from the various branches that connect each 1st level node a, to all 2nd level nodes b associated with the stream connection.

$$\sum_{b=1}^{Y_{rp}} D_{rp}^{a,b} = D_{rp}^{a} \quad \forall a \in X_{rp};\ \forall r \in R;\ \forall p \in P \tag{169}$$

The flows allocated from each of the 1st level nodes in the stream that connects the wastewater mains and centralized treatment facility s of type t (D_{st}^{a}) must equal the summation of all flows $\left(D_{st}^{a,b}\right)$ from the various branches that connect each 1st level node a, to all 2nd level nodes b associated with the stream connection.

$$\sum_{b=1}^{Y_{st}} D_{st}^{a,b} = D_{st}^{a} \quad \forall a \in X_{st}; \forall s \in S;\ \forall t \in T \tag{170}$$

The flows allocated from each of the 2nd level nodes in the stream that connects sink j in plant p' and decentralized treatment facility r in plant p ($T_{rp,jp'}^{a,b}$) must equal the summation of all flows $\left(T_{rp,jp'}^{a,b,c}\right)$ from the various branches that connect each 2nd level node b, to all 3rd level nodes *c* associated with the stream connection.

$$\sum_{c=1}^{Z_{rp,jp'}} T_{rp,jp'}^{a,b,c} = T_{rp,jp'}^{a,b} \quad \forall a \in X_{rp,jp'}; \forall b \in Y_{rp,jp'}; \forall j \in SN_p;\ \forall p,p' \in P;\ \forall r \in R \tag{171}$$

The flows allocated from each of the 2nd level nodes in the stream that connects sink j in plant p' and centralized treatment facility s of type t ($T_{st,jp}^{a,b}$) must equal the summation of all flows $\left(T_{st,jp}^{a,b,c}\right)$ from the various branches that connect each 2nd level node b, to all 3rd level nodes *c* associated with the stream connection.

$$\sum_{c=1}^{Z_{st,jp}} T_{st,jp}^{a,b,c} = T_{st,jp}^{a,b} \quad \forall a \in X_{st,jp}; \forall b \in Y_{st,jp}; \forall j \in SN_p;\ \forall p \in P;\ \forall s \in S;\ \forall t \in T \tag{172}$$

The flows allocated from each of the 2nd level nodes in the stream that connects the wastewater mains and decentralized treatment facility r in plant p ($D_{rp}^{a,b}$) must equal the summation of all flows $\left(D_{rp}^{a,b,c}\right)$ from the various branches that connect each 2nd level node *b*, to all 3rd level nodes *c* associated with the stream connection.

$$\sum_{c=1}^{Z_{rp}} D_{rp}^{a,b,c} = D_{rp}^{a,b} \quad \forall a \in X_{rp};\ \forall b \in Y_{rp}; \forall r \in R;\ \forall p \in P \tag{173}$$

The flows allocated from each of the 2nd level nodes in the stream that connects the wastewater mains and centralized treatment facility s of type t ($D_{st}^{a,b}$) must equal the summation of all flows $\left(D_{st}^{a,b,c}\right)$ from the various branches that connect each 2nd level node *b*, to all 3rd level nodes *c* associated with the stream connection.

$$\sum_{c=1}^{Z_{st}} D_{st}^{a,b,c} = D_{st}^{a,b} \quad \forall a \in X_{st}; \forall b \in Y_{st}; \forall s \in S;\ \forall t \in T \tag{174}$$

The flows allocated from each of the (n-1)th level nodes in the stream that connects sink j in plant p' and decentralized treatment facility r in plant p ($T_{rp,jp'}^{a,b,c,..,n-1}$) must equal the summation of all flows $\left(T_{rp,jp'}^{a,b,c,..,n-1,n}\right)$ from the various branches that connect each (n-1)th level node, to all nth level nodes associated with the stream connection.

$$\sum_{n=1}^{N_{rp,jp'}} T_{rp,jp'}^{a,b,c,..,n-1,n} = T_{rp,jp'}^{a,b,c,..,n-1} \quad \forall a \in X_{rp,jp'}; \forall b \in Y_{rp,jp'}; \forall c \in Z_{rp,jp'} .. \forall (n-1) \in (N-1)_{rp,jp'}; \forall j \in SN_p;\ \forall p, p' \in P;\ \forall r \in R \tag{175}$$

The flows allocated from each of the (n-1)th level nodes in the stream that connects sink j in plant p' and centralized treatment facility s of type t ($T_{st,jp}^{a,b,c,..,n-1}$) must equal the summation of all flows $\left(T_{st,jp}^{a,b,c,..,n-1,n}\right)$ from the various branches that connect each (n-1)th level node, to all nth level nodes associated with the stream connection.

$\sum_{n=1}^{N_{st,jp}} T_{st,jp}^{a,b,c,..,n-1,n} = T_{st,jp}^{a,b,c,..,n-1} \quad \forall a \in X_{st,jp}; \forall b \in Y_{st,jp}; \forall c \in Z_{st,jp'} \,..\, \forall(n-1) \in (N-1)_{st,jp'}; \forall j \in SN_p;\ \forall p \in P;\ \forall s \in S;\ \forall t \in T$ (176)

The flows allocated from each of the (n-1)th level nodes in the stream that connects the wastewater mains and decentralized treatment facility r in plant p ($D_{rp}^{a,b,c,..,n-1}$) must equal the summation of all flows $\left(D_{rp}^{a,b,c,..,n-1,n}\right)$ from the various branches that connect each (n-1)th level node, to all nth level nodes associated with the stream connection.

$\sum_{n=1}^{N_{rp}} D_{rp}^{a,b,c,..,n-1,n} = D_{rp}^{a,b,c,..,n-1} \quad \forall a \in X_{rp};\ \forall b \in Y_{rp}; \forall c \in Z_{rp} \,..\, \forall(n-1) \in (N-1)_{rp}; \forall r \in R;\ \forall p \in P$ (177)

The flows allocated from each of the (n-1)th level nodes in the stream that connects the wastewater mains and centralized treatment facility s of type t ($D_{st}^{a,b,c,..,n-1}$) must equal the summation of all flows $\left(D_{st}^{a,b,c,..,n-1,n}\right)$ from the various branches that connect each (n-1)th level node, to all nth level nodes associated with the stream connection.

$\sum_{n=1}^{N_{st}} D_{st}^{a,b,c,..,n-1,n} = D_{st}^{a,b,c,..,n-1} \quad \forall a \in X_{st}; \forall b \in Y_{st}; \forall c \in Z_{st} \,..\, \forall(n-1) \in (N-1)_{st}; \forall s \in S;\ \forall t \in T$ (178)

The flow to sink j in plant p' from a 1st level node *a* that receives flow from a decentralized treatment facility r in plant p ($T_{rp,jp\prime}^{a}$) must be equal to the flow associated with the same 1st level node a connecting any other decentralized treatment facility r' in plant p to the same sink j in plant p' ($T^{a}_{r'p,jp'}$).

$$T^{a}_{rp,jp'} = T^{a}_{r'p,jp'}\ \forall j \in SN_p; \forall p, p' \in P; \forall (r, r') \in R;\ \forall a \in X_{rp,jp'} \tag{179}$$

The flow to sink j in plant p from a 1st level node a that eventually connects to a centralized treatment facility s of type t ($T^{a}_{st,jp}$) must be equal to the flow associated with the same 1st level node a connecting any other centralized treatment facility s' of type t' to the same sink j in plant p ($T^{a}_{s't',jp}$).

$$T^{a}_{st,jp} = T^{a}_{s't',jp}\ \forall j \in SN_p; \forall p \in P; \forall (s, s') \in S;\ \forall (t, t') \in T;\ \forall a \in X_{st,jp} \tag{180}$$

The flow to the wastewater mains from a 1st level node a that receives flow from a decentralized treatment facility r in plant p(D^{a}_{rp}) must be equal to the flow associated with the same 1st level node connecting any other decentralized treatment facility r' in plant p' to the waste mains ($D^{a}_{r',p'}$).

$$D^{a}_{rp} = D^{a}_{r',p'}\ \forall (r, r') \in R;\ \forall (p, p') \in P; \forall a \in X_{rp} \tag{181}$$

The flow to the wastewater mains from a 1st level node a that receives flow from a centralized treatment facility s of type t (D^{a}_{st}) must be equal to the flow associated with the same 1st level node connecting any other centralized treatment facility s' of type t' to the waste mains ($D^{a}_{s't'}$).

$$D^{a}_{st} = D^{a}_{s',t'}\ \forall (s, s') \in S;\ \forall (t, t') \in T; \forall a \in X_{st} \tag{182}$$

The flow to sink j in plant p' from a 2nd level node b that receives flow through a 1st level node a that eventually connects back to a decentralized treatment facility r in plant p ($T_{rp,jp'}^{a,b}$) must be equal to the flow associated with that 2nd level node *b* through the same 1st level node *a* connecting any other decentralized treatment facility r' in plant p to the same sink j in plant p' ($T_{r'p,jp'}^{a,b}$).

$$T_{rp,jp'}^{a,b} = T_{r'p,jp'}^{a,b}\ \forall j \in SN_p; \forall p,p' \in P; \forall (r,r') \in R;\ \forall a \in X_{rp,jp'}; \forall b \in Y_{rp,jp'} \quad (183)$$

The flow to sink j in plant p from a 2nd level node *b* that receives flow through a 1st level node *a* that eventually connects back to a centralized treatment facility s of type t ($T_{st,jp}^{a,b}$) must be equal to the flow associated with that 2nd level node *b* through the same 1st level node *a* connecting any other centralized treatment facility s' of type t' to the same sink j in plant p ($T_{s't',jp}^{a,b}$).

$$T_{st,jp}^{a,b} = T_{s't',jp}^{a,b}\ \forall j \in SN_p; \forall p \in P; \forall (s,s') \in S;\ \forall (t,t') \in T;\ \forall a \in X_{st,jp};\ \forall b \in Y_{st,jp} \quad (184)$$

The flow to the wastewater mains from a 2nd level node *b* that receives flow through a 1st level node *a* that eventually connects back to a decentralized treatment facility r in plant p($D_{rp}^{a,b}$) must be equal to the flow associated with that 2nd level node *b* through the same 1st level node *a* connecting any other decentralized treatment facility r' in plant p' to the waste mains($D_{r',p'}^{a,b}$).

$$D_{rp}^{a,b} = D_{r',p'}^{a,b}\ \forall (r,r') \in R;\ \forall (p,p') \in P; \forall a \in X_{rp}; \forall b \in Y_{rp} \quad (185)$$

The flow to the wastewater mains from a 2nd level node *b* that receives flow through a 1st level node *a* that eventually connects back to a centralized treatment facility s of type t ($D_{st}^{a,b}$) must be equal to the flow associated with that 2nd level node *b* through the same 1st level node *a* connecting any other centralized treatment facility s' of type t' to the waste mains ($D_{s\prime t\prime}^{a,b}$).

$$D_{st}^{a,b} = D_{s\prime,t\prime}^{a,b}\ \forall(s,s') \in S;\ \forall(t,t') \in T; \forall a \in X_{st}; \forall b \in Y_{st} \tag{186}$$

The flow to sink j in plant p' from a 3rd level node *c* that receives flow through a 2nd level node *b* and a 1st level node *a* that eventually connects back to a decentralized treatment facility r in plant p ($T_{rp,jp\prime}^{a,b,c}$) must be equal to the flow associated with that 3rd level node c through the same 2nd level node *b* and 1st level node *a* connecting any other decentralized treatment facility r' in plant p to the same sink j in plant p' ($T_{r'p,jp'}^{a,b,c}$).

$$T_{rp,jp\prime}^{a,b,c} = T_{r\prime p,jp\prime}^{a,b,c}\ \forall j \in SN_p; \forall p,p' \in P; \forall(r,r') \in R;\ \forall a \in X_{rp,jp'}; \forall b \in Y_{rp,jp'}; \forall c \in Z_{rp,jp\prime} \tag{187}$$

The flow to sink j in plant p from a 3rd level node *c* that receives flow through a 2nd level node *b* and a 1st level node *a* that eventually connects back to a centralized treatment facility s of type t ($T_{st,jp}^{a,b,c}$) must be equal to the flow associated with that 3rd level node c through the same 2nd level node *b* and 1st level node *a* connecting any other centralized treatment facility s' of type t' to the same sink j in plant p ($T_{s\prime t\prime,jp}^{a,b,c}$).

$$T_{st,jp}^{a,b,c} = T_{s\prime t\prime,jp}^{a,b,c}\ \forall j \in SN_p; \forall p \in P; \forall(s,s') \in S;\ \forall(t,t') \in T;\ \forall a \in X_{st,jp};\ \forall b \in Y_{st,jp};\ \forall c \in Z_{st,jp} \tag{188}$$

The flow to the wastewater mains from a 3rd level node *c* that receives flow through a 2nd level node *b* and a 1st level node *a* that eventually connects back to a decentralized treatment facility r in plant p($D_{rp}^{a,b,c}$) must be equal to the flow associated with that 3rd level node c through the same 2nd level node *b* and 1st level node *a* connecting any other decentralized treatment facility r' in plant p' to the waste mains($D_{r\prime,p\prime}^{a,b,c}$).

$$D_{rp}^{a,b,c} = D_{r\prime,p\prime}^{a,b,c} \; \forall(r, r') \in R;\; \forall(p, p') \in P; \forall a \in X_{rp}; \forall b \in Y_{rp}; \forall c \in Z_{rp} \tag{189}$$

The flow to the wastewater mains from a 3rd level node *c* that receives flow through a 2nd level node *b* and a 1st level node *a* that eventually connects back to a centralized treatment facility s of type t ($D_{st}^{a,b,c}$) must be equal to the flow associated with that 3rd level node c through the same 2nd level node *b* and 1st level node *a* connecting any other centralized treatment facility s' of type t' to the waste mains($D_{s\prime t\prime}^{a,b,c}$).

$$D_{st}^{a,b,c} = D_{s\prime,t\prime}^{a,b,c} \; \forall(s, s') \in S;\; \forall(t, t') \in T; \forall a \in X_{st}; \forall b \in Y_{st}; \forall c \in Z_{st} \tag{190}$$

The flow to sink j in plant p' from an nth level node *n* through an (n-1)th level node *(n-1)* all the way to a 1st level node *a* that eventually connects back to a decentralized treatment facility r in plant p ($T_{rp,jp\prime}^{a,b,c,..,n-1,n}$) must be equal to the flow associated with that nth level node *n* through the same (n-1)th level node *(n-1)* all the way to the 1st level node *a* connecting any other decentralized treatment facility r' in plant p to the same sink j in plant p' ($T_{r'p,jp'}^{a,b,c,..,n-1,n}$).

$T_{rp,jp'}^{a,b,c,..,n-1,n} = T_{r'p,jp'}^{a,b,c,..,n-1,n}\ \forall j \in SN_p; \forall p, p' \in P; \forall (r, r') \in R;\ \forall a \in X_{rp,jp'}; \forall b \in Y_{rp,jp'}; \forall c \in Z_{rp,jp'} .. \forall (n-1) \in (N-1)_{rp,jp'}; \forall n \in N_{rp.jp'}$ (191)

The flow to sink j in plant p from an n^{th} level node *n* through an $(n\text{-}1)^{th}$ level node *(n-1)* all the way to a 1^{st} level node *a* that eventually connects back to a centralized treatment facility s of type t ($T_{st,jp}^{a,b,c,..,n-1,n}$) must be equal to the flow associated with that n^{th} level node *n* through the same $(n\text{-}1)^{th}$ level node *(n-1)* all the way to the 1^{st} level node *a* connecting any other centralized treatment facility s' of type t' to the same sink j in plant p ($T_{s't',jp}^{a,b,c,..,n-1,n}$).

$T_{st,jp}^{a,b,c,..,n-1,n} = T_{s't',jp}^{a,b,c,..,n-1,n}\ \forall j \in SN_p; \forall p \in P; \forall (s, s') \in S;\ \forall (t, t') \in T;\ \forall a \in X_{st,jp};\ \forall b \in Y_{st,jp};\ \forall c \in Z_{st,jp} .. \forall (n-1) \in (N-1)_{st,jp}; \forall n \in N_{st,jp}$ (192)

The flow to the wastewater mains from an n^{th} level node *n* through an $(n\text{-}1)^{th}$ level node *(n-1)* all the way to a 1^{st} level node *a* that eventually connects back to a decentralized treatment facility r in plant p($D_{rp}^{a,b,c,..,n-1,n}$) must be equal to the flow associated with that 3^{rd} level node c through the same 2^{nd} level node *b* and 1^{st} level node *a* connecting any other decentralized treatment facility r' in plant p' to the waste mains ($D_{r',p'}^{a,b,c,..,n-1,n}$).

$D_{rp}^{a,b,c,..,n-1,n} = D_{r',p'}^{a,b,c,..,n-1,n}\ \forall (r, r') \in R;\ \forall (p, p') \in P; \forall a \in X_{rp}; \forall b \in Y_{rp}; \forall c \in Z_{rp} .. \forall (n-1) \in (N-1)_{rp}; \forall n \in N_{rp}$ (193)

The flow to the wastewater mains from an n^{th} level node *n* through an $(n-1)^{th}$ level node *(n-1)* all the way to a 1^{st} level node *a* that eventually connects back to a centralized treatment facility s of type t ($D_{st}^{a,b,c,..,n-1,n}$) must be equal to the flow associated with that n^{th} level node *n* through the same $(n-1)^{th}$ level node *(n-1)* all the way to the 1^{st} level node *a* connecting any other centralized treatment facility s' of type t' to the waste mains ($D_{s't'}^{a,b,c,..,n-1,n}$).

$$D_{st}^{a,b,c,..,n-1,n} = D_{s',t'}^{a,b,c,..,n-1,n} \; \forall (s, s') \in S;\; \forall (t, t') \in T; \forall a \in X_{st}; \forall b \in Y_{st}; \forall c \in Z_{st} \,..\, \forall (n-1) \in (N-1)_{st}; \forall n \in N_{st} \tag{194}$$

Additionally, the total flows across all branches whether connecting a de-central treatment facility r within a plant p to a sink j in plant p', or connecting a shared central treatment facility s of type t to a sink j in plant p, must all be equal to the individual sum of all flows across each of the branches that establish the connection, respectively:

$$T_{rp,jp'}^{a} + T_{rp,jp'}^{a,b} + T_{rp,jp'}^{a,b,c} + \cdots + T_{rp,jp'}^{a,b,c,..,n} = T_{rp,jp'} \; \forall j \in SN_p; \forall p, p' \in P; \forall r \in R; \forall a \in X_{rp,jp'}; \forall b \in Y_{rp,jp'}; \forall c \in Z_{rp,jp'} .. \forall n \in N_{rp,jp'} \tag{195}$$

$$T_{st,jp}^{a} + T_{st,jp}^{a,b} + T_{st,jp}^{a,b,c} + \cdots + T_{st,jp}^{a,b,c,..,n} = T_{st,jp} \; \forall j \in SN_p; \forall p \in P; \forall s \in S; \forall t \in T; \forall a \in X_{st,jp}; \forall b \in Y_{st,jp}; \forall c \in Z_{st,jp} .. \forall n \in N_{st,jp} \tag{196}$$

Moreover, the total flows across all branches connecting either a de-central treatment facility r within a plant p to the wastewater mains, or a central treatment facility s of type t to the wastewater mains must respectively be equal to the individual sum of all flows across each of the branches that establish the connection:

$$D_{rp}^{a} + D_{rp}^{a,b} + D_{rp}^{a,b,c} + \cdots + \ D_{rp}^{a,b,c,..,n} = D_{rp}\ \forall i \in SU_p;\ \forall p \in P; \forall a \in X_{rp}\ ; \forall b \in Y_{rp}\ ; \forall c \in Z_{rp} .. \forall n \in N_{st} \quad (197)$$

$$D_{st}^{a} + D_{st}^{a,b} + D_{st}^{a,b,c} + \cdots + \ D_{st}^{a,b,c,..,n} = D_{st}\ \forall i \in SU_p;\ \forall p \in P; \forall a \in X_{st}\ ; \forall b \in Y_{st}\ ; \forall c \in Z_{st} .. \forall n \in N_{st} \quad (198)$$

In addition, non-negative constraints must be maintained for all flows across any branch associated with establishing a connection from a de-central treatment facility r in plant p to sink j in plant p'.

$$T_{rp,jp'}^{a} \geq 0\ \forall j \in SN_p; \forall p, p' \in P; \forall r \in R; \forall a \in X_{rp,jp'} \quad (199)$$

$$T_{rp,jp'}^{a,b} \geq 0\ \forall j \in SN_p; \forall p, p' \in P; \forall r \in R; \forall a \in X_{rp,jp'}; \forall b \in Y_{rp,jp'} \quad (200)$$

$$T_{rp,jp'}^{a,b,c} \geq 0\ \forall j \in SN_p; \forall p, p' \in P; \forall r \in R; \forall a \in X_{rp,jp'}; \forall b \in Y_{rp,jp'}\ ; \forall c \in Z_{rp,jp'} \quad (201)$$

…

$$T_{rp,jp'}^{a,b,c,..,n} \geq 0\ \forall j \in SN_p; \forall p, p' \in P; \forall r \in R; \forall a \in X_{rp,jp'}; \forall a \in X_{rp,jp'}\ ; \forall b \in Y_{rp,jp'}\ ; \forall c \in Z_{rp,jp'} .. \forall n \in N_{rp,jp'} \quad (202)$$

Similarly, non-negative constraints must be maintained for all flows across any branch associated with establishing a connection from a central treatment facility s of type t to a sink j in plant p.

$$T_{st,jp}^{a} \geq 0\ \forall j \in SN_p;\ \forall p \in P; \forall s \in S; \forall t \in T; \forall a \in X_{st,jp} \quad (203)$$

$$T_{st,jp}^{a,b} \geq 0\ \forall j \in SN_p;\ \forall p \in P; \forall s \in S; \forall t \in T; \forall a \in X_{st,jp}; \forall b \in Y_{st,jp} \quad (204)$$

$T_{st,jp}^{a,b,c} \geq 0 \forall j \in SN_p;\ \forall p \in P; \forall s \in S; \forall t \in T; \forall a \in X_{st,jp}; \forall b \in Y_{st,jp}\ ; \forall c \in Z_{st,jp}$

(205)

…

$T_{st,jp}^{a,b,c,..,n} \geq 0\ \forall j \in SN_p;\ \forall p \in P; \forall s \in S; \forall t \in T; \forall a \in X_{st,jp}\ ; \forall b \in Y_{st,jp}\ ; \forall c \in$
$Z_{st,jp} . . \forall n \in N_{st,jp}$ (206)

Moreover, non-negative constraints are required for flows across any branch associated with establishing a connection from a decentralized treatment facility r in plant p to the wastewater mains.

$D_{rp}^{a} \geq 0\ \forall i \in SU_p;\ \forall i \in SU_p;\ \forall p \in P; \forall a \in X_{rp}$ (207)

$D_{rp}^{a,b} \geq 0\ \forall i \in SU_p;\ \forall i \in SU_p;\ \forall p \in P; \forall a \in X_{rp}; \forall b \in Y_{rp}$ (208)

$D_{rp}^{a,b,c} \geq 0\ \forall i \in SU_p;\ \forall i \in SU_p;\ \forall p \in P; \forall a \in X_{rp}; \forall b \in Y_{rp}\ ; \forall c \in Z_{rp}$

(209)

…

$D_{rp}^{a,b,c,..,n} \geq 0\ \forall i \in SU_p;\ \forall i \in SU_p;\ \forall p \in P; \forall a \in X_{rp}\ ; \forall b \in Y_{rp}\ ; \forall c \in Z_{rp} . . \forall n \in N_{rp}$

(210)

Lastly, non-negative constraints are required for flows across any branch associated with establishing a connection from a centralized treatment facility s of type t to the wastewater mains

$D_{st}^{a} \geq 0\ \forall i \in SU_p;\ \forall i \in SU_p;\ \forall p \in P; \forall a \in X_{st}$ (211)

$D_{st}^{a,b} \geq 0\ \forall i \in SU_p;\ \forall i \in SU_p;\ \forall p \in P; \forall a \in X_{st}; \forall b \in Y_{st}$ (212)

$$D_{st}^{a,b,c} \geq 0\ \forall i \in SU_p;\ \forall i \in SU_p;\ \forall p \in P; \forall a \in X_{st}; \forall b \in Y_{st}\ ; \forall c \in Z_{st} \tag{213}$$

…

$$D_{st}^{a,b,c,..,n} \geq 0\ \forall i \in SU_p;\ \forall i \in SU_p;\ \forall p \in P; \forall a \in X_{st}; \forall b \in Y_{st}\ ; \forall c \in Z_{st} .. \forall n \in N_{st} \tag{214}$$

V.3.3 Implementation

The problem described above has been formulated as a mixed integer nonlinear optimization problem (MINLP) for treatment and direct recycling. The corresponding water allocation strategy has been obtained using "what'sBest9.0.5.0" LINDO Global Solver for Microsoft Excel 2010, using a desktop PC with Intel® Core ™ i7-2620M, 2.7 GHz, 8.00 GB RAM, and a 64-bit Operating System.

V.4. Illustrative Case Study

An artificial case study, described in this section, has been carried out to demonstrate the proposed methodology. Figure 35 provides the layout of the industrial zone that has been assumed.

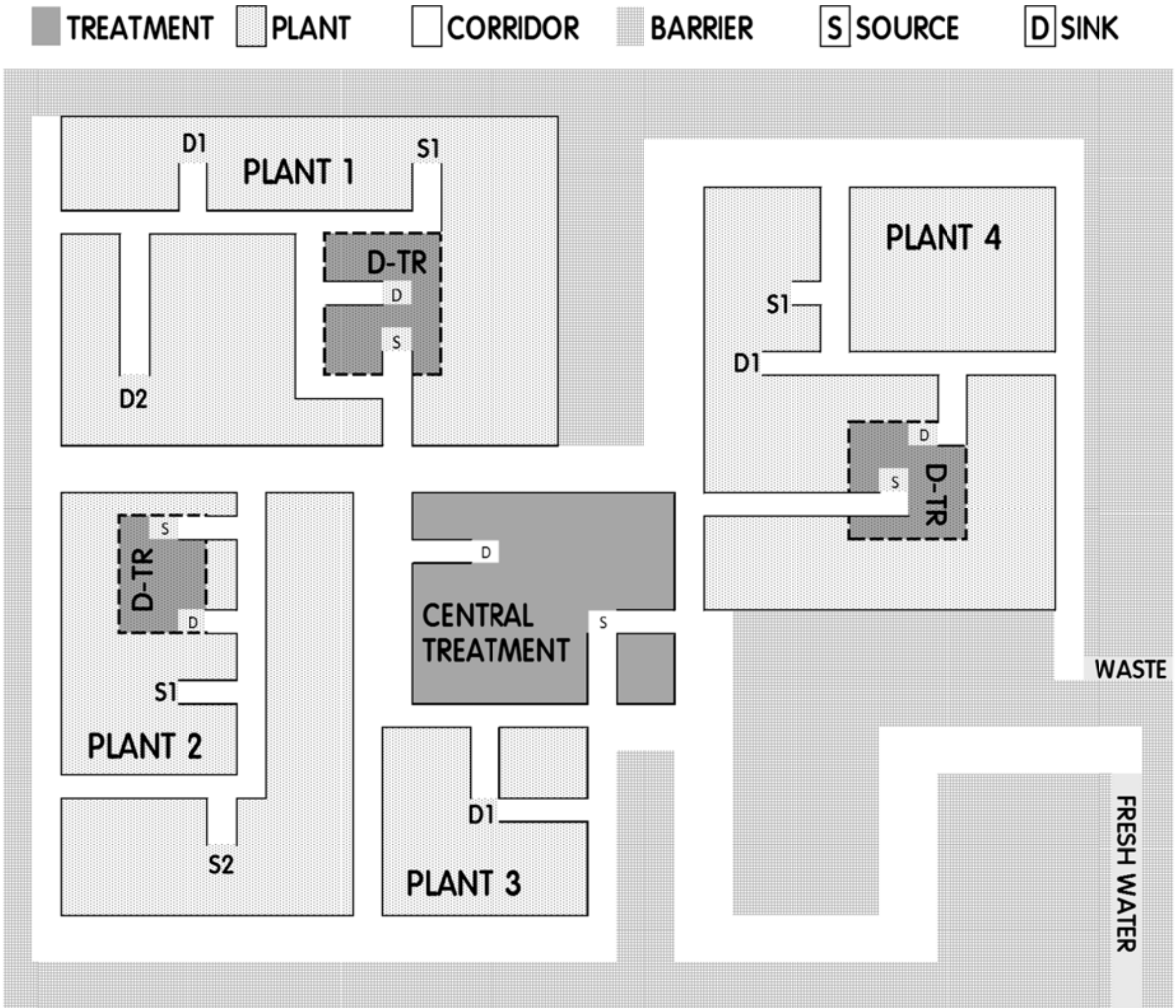

Figure 35. Case Study Layout

A total of 4 co-locating plants are incorporated, 3 of which involve an on-site wastewater treatment facility. Additionally, a centralized treatment unit shared amongst all plants has also been provided, for which a specified treatment option can be selected. The total area of the region was assumed to be 64 km^2, and the respective plants were assumed to span a total area of 17.25 km^2, according to the following distribution: area of plant 1= 5.95 km^2; area of plant 2= 4.5 $km^{2;}$ area of plant 3= 1.4 km^2; and area of plant 4= 5.4 km^2. Table 42 provides the case study flowrate and composition data for all available source and sink water streams. Varying amounts of three different contaminants were assumed to be present in all process water streams, hence, 3 pollutant concentrations for each have been provided for this case study. Moreover, a maximum inlet concentration for each water sink has also been specified, for the same pollutants indicated in the all water source streams. Table 43 outlines all contaminant removal ratios, as well as the corresponding fixed and operating cost elements that are associated with the decentralized treatment units, as well as the centralized treatment option. It can be noted that Plants 1, 2 and 4 were associated with their own on-site wastewater treatment units.

Table 42. Water Sink and Source Data

Sink	**Flow**	**Zmax 1**	**Zmax 2**	**Zmax 3**	**Source**	**Flow**	**Y 1**	**Y2**	**Y3**
	t/d	ppm	ppm	ppm		t/d	ppm	ppm	ppm
P1D1	180	50	50	60	**P1S1**	100	100	80	50
P1D2	150	90	80	50	**P2S1**	70	120	130	110
P3D1	90	100	70	60	**P2S2**	160	170	130	180

Table 43. Wastewater treatment parameters in terms of pollutant removal ratios, and costs

Interceptor	Y 1	Y 2	Y 3	CAP.EX ($)	OP.EX ($-kg)
TR-P1	0.7	0.6	0	0	0.203
TR-P2	0.8	0	0.6	0	0.444
TR-P4	0	0.9	0.8	0	0.752
CTR-1	0.9	0.9	0.9	12,400	0.908

Additional information requirements that have been specified for all plants involve the following: (1) freshwater cost =0.13 $/t, (2) waste disposal cost =0.9 $/t, and (3) operating hours =8760 h/y. Moreover, carbon steel Schedule 80 welded pipes were assumed for all designs, and the calculated pipeline diameters were rounded up in increments of 0.1, to the nearest standard size in meters. All piping costs were annualized over a 20-year lifetime. In this case study, both forward branching as well as backward branching has been applied for the purpose of pipeline merging. Each branching case has been investigated using two types of pipeline bending options: (1) allowing only 90^0 pipeline bends and (2) allowing 45^0 , 90^0 and 135^0 pipeline bends throughout the design. In doing so, a specific set of constraints have been imposed on the pipeline route extraction process. This procedure has been described in our previous work (Alnouri, Linke et al. 2010a).

As per the descriptions for this case study, a total of 4 scenarios have been implemented for the purpose of illustration. Case 1 applies a forward branching scenario for pipeline merging, allowing only 90^0 bends in the design. Case 2 applies the same forward branching scheme, but allows more flexibility by implementing 45^0 , 90^0 and 135^0 pipeline bends throughout. Case 3 on the other hand applies a backward branching scenario, using only 90^0 pipeline bends. Lastly, Case 4 adopts a similar setup to Case 2, only to utilize a backward branching scheme for pipeline merging instead. For all cases described above, the overall source-interceptor-sink water allocations have been reported. Table 44 summarizes the respective flowrates for allocation strategy attained. However, much of the differences in the designs lie in the branching schemes attained. Figures 36 and 37 illustrate the pipeline merging scenario that have been achieved via forward branching for Cases 1 and 2, respectively. Figures 38 and 39 illustrate the pipeline merging scenario that have been achieved via backward branching for Cases 3 and 4, respectively. The main differences in the designs obtained for Cases 1 and 2 were the pipeline bending procedure involved. The nodes at which branching were to occur were mostly different. A similar trend was observed when comparing Cases 3 and 4.

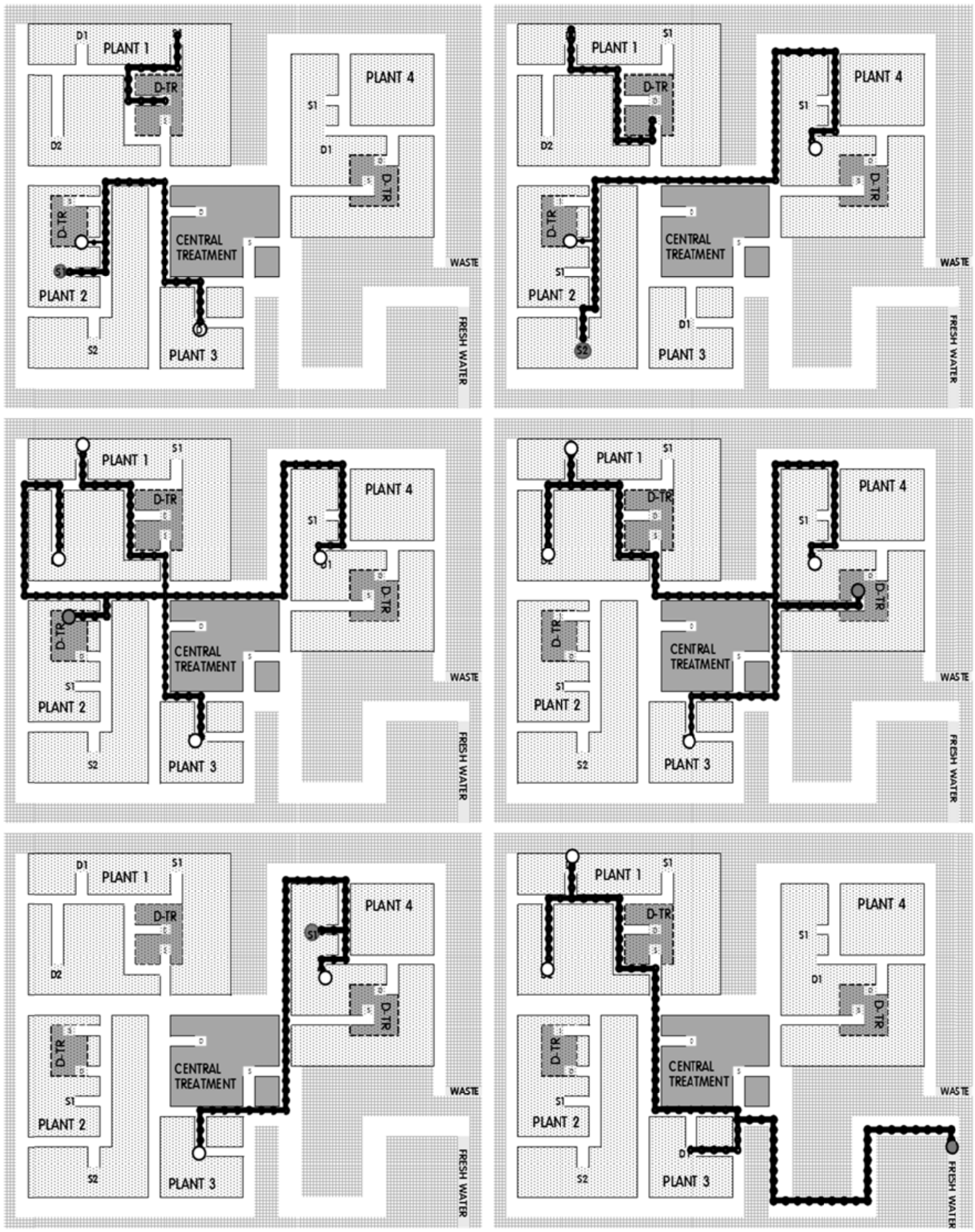

Figure 36. Forward pipeline branching with 90^0 pipe bending illustrated (Case 1)

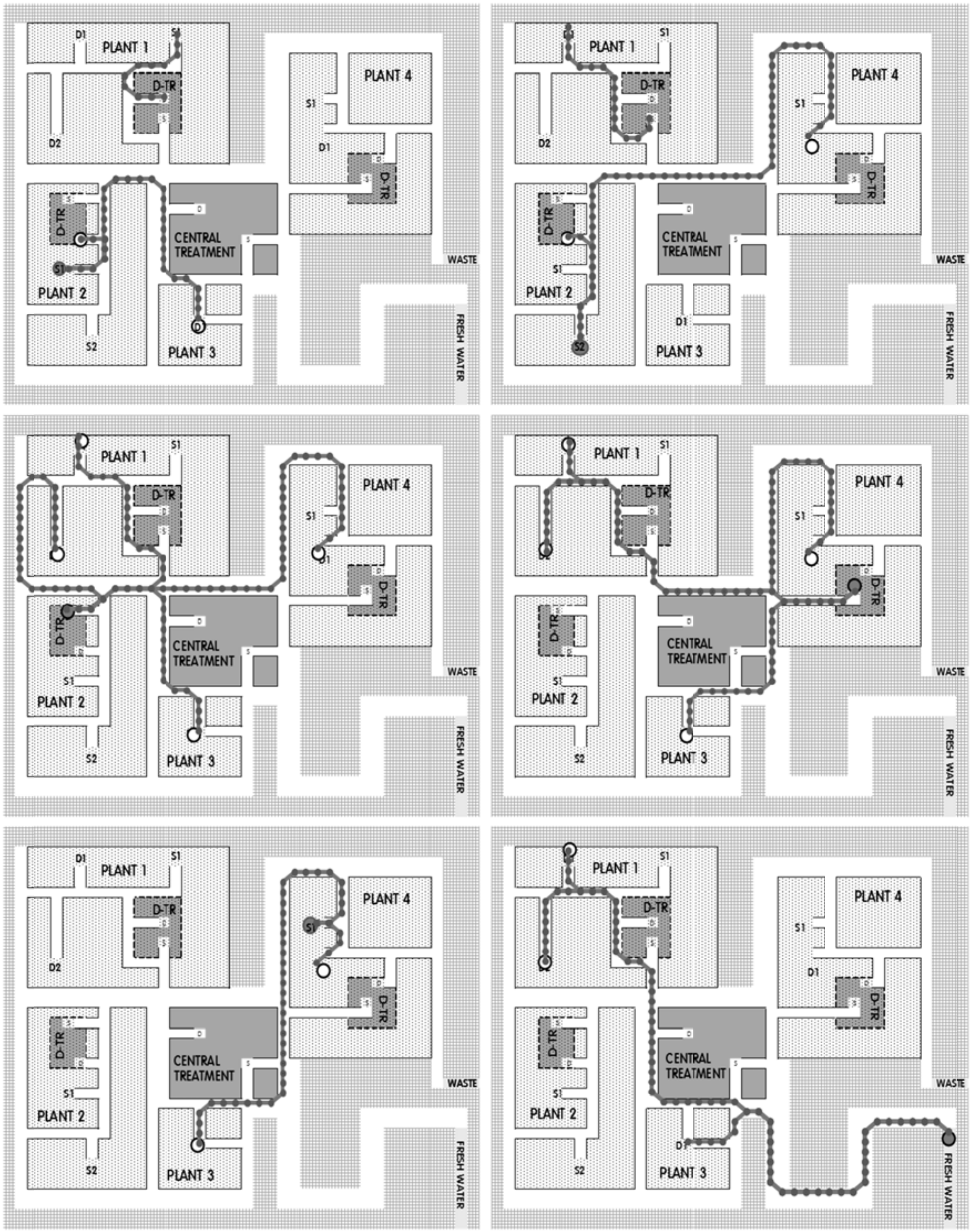

Figure 37. Forward pipeline branching with 90^0, 45^0 and 135^0 pipe bending illustrated (Case 2)

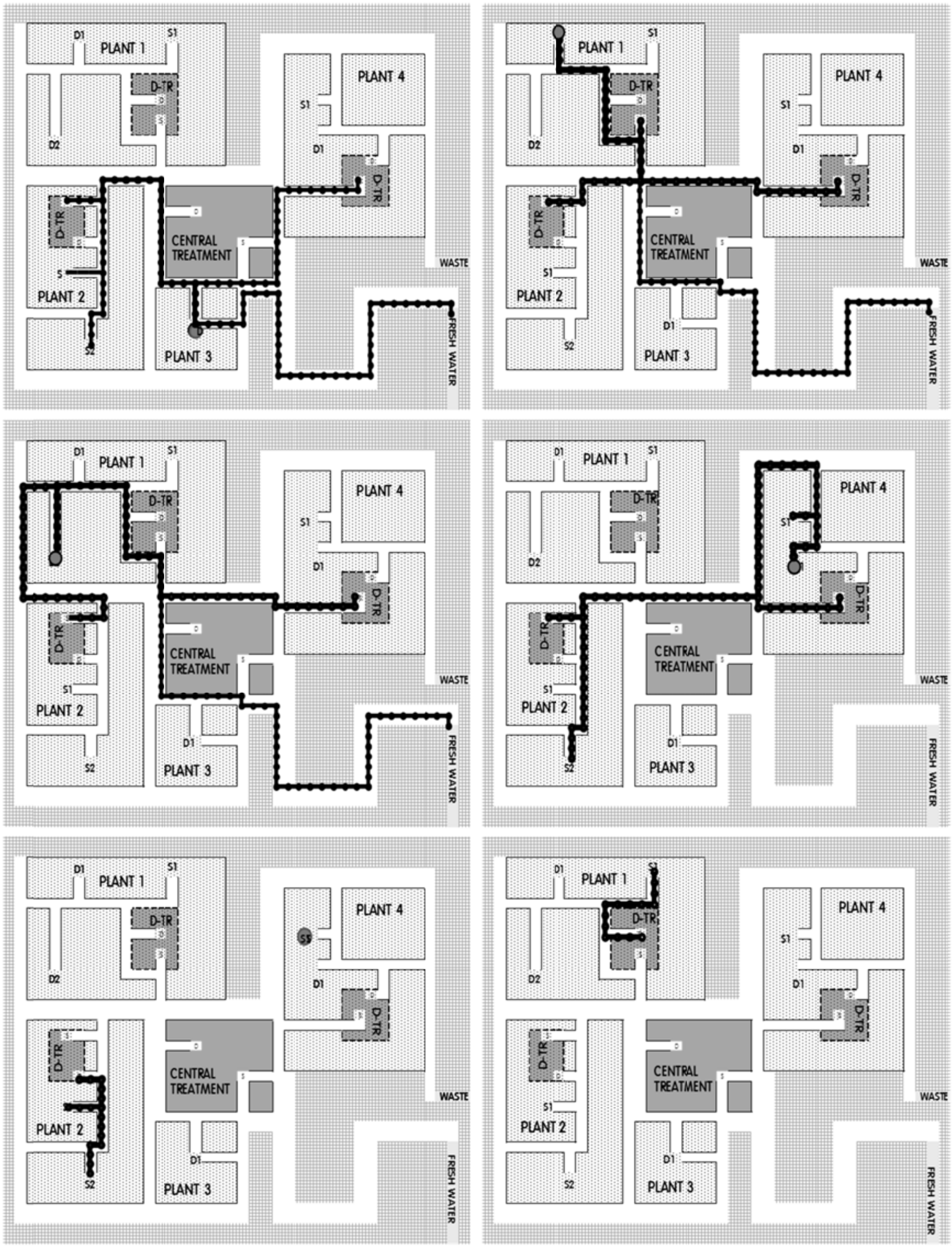

Figure 38. Backward pipeline branching with 90^0 bending illustrated (Case 3)

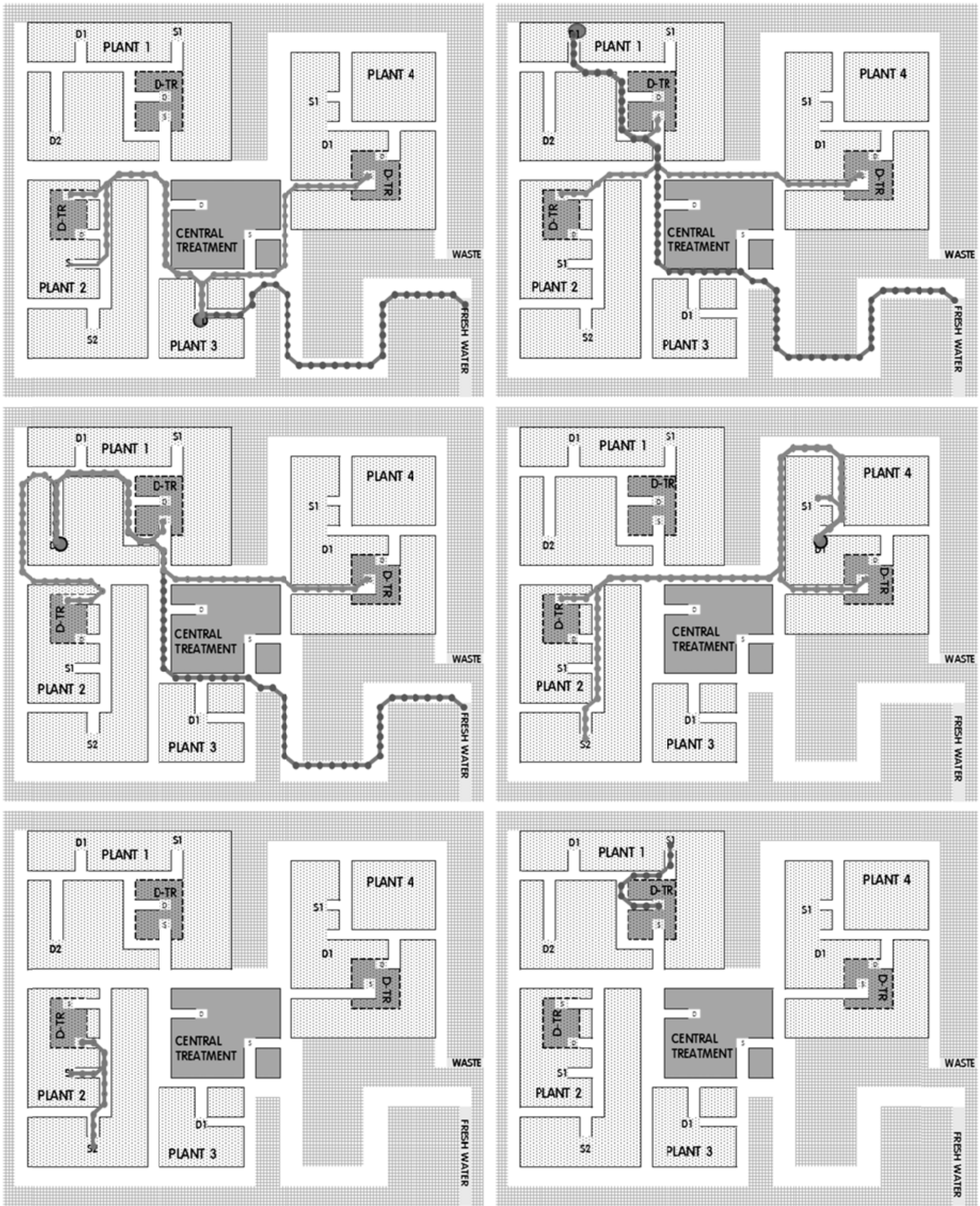

Figure 39. Backward pipeline branching with 90^0, 45^0 and 135^0 pipe bending illustrated (Case 4)

Table 44. Water allocation obtained for Cases 1-4

	P1D1	**P1D2**	**P3D1**	**P4D1**	**TR-P1**	**TR-P2**	**TR-P4**	**C-TR**
P1S1	0	0	0	0	100.00	0	0	0
P2S1	0	0	10.51	0	0	59.49	0	0
P2S2	0	0	0	9.69	0	150.31	0	0
P4S1	0	0	5.51	8.94	0	0	115.56	0
TR-P1	100.00	0	0	0	0	0	0	0
TR-P2	41.32	84.71	28.08	55.69	0	0	0	0
TR-P4	21.42	49.36	9.09	35.69	0	0	0	0
C-TR	0	0	0	0	0	0	0	0

It can be noted that decentralized treatment was primarily utilized in Plants 1,2 and 4, and the utilization of a centralized treatment facility was found to be necessary in this case. In all 4 cases, freshwater consumption was found to be 70 t/h, while no wastewater discharge was obtained. Table 45 summarizes the cost breakdown of the water network designs attained. The total treatment costs and freshwater costs were found to be 4.66×10^5\$/yr and 7.97×10^4 \$/yr respectively. Moreover, no wastewater disposal costs were reported. A comparison of the total annualized costs were summarized for all cases, when no pipeline merging was involved. According to the results presented in Table 45, it is evident that total costs were found to decrease when pipeline merging was implemented, allowing up to 5.64% savings on pipeline costs, when compared to the standard unmerged pipeline costs.

Table 45. Summary of Costs obtained for Cases 1-4

($/y)	Forward Branching, 90^0 Bends only	Forward Branching, 90^0, 45^0 and 135^0 Bends	Backward Branching, 90^0 Bends only	Backward Branching, 90^0, 45^0 and 135^0 Bends
Freshwater Costs	79,716	79,716	79,716	79,716
Treatment Costs	466,022	466,022	466,022	466,022
Wastewater Disposal Costs	0	0	0	0
Pipeline Costs- Unmerged	493,603	436,702	493,603	436,702
Total Costs- Unmerged Scenario	1,039,341	982,440	1,039,341	982,440
Pipeline Costs- Unmerged	438,059	400,221	449,655	407,028
Total Costs- Merged Scenario	983,798	945,959	995,393	952,766
% Savings on pipeline costs	12.68	9.12	9.77	7.29
% Savings on total costs	5.65	3.86	4.42	3.11

Moreover, it was also found that allowing more pipeline bending opportunities help improve the cost performance of the designs achieved. When comparing the total costs achieved in Cases 1 and 2, Case 2 yielded a total of 4.01% of total cost improvement (corresponding to a 9.45% pipeline cost savings). Similarly, comparing the total costs achieved in Cases 3 and 4, Case 3 yielded a total of 4.47% of total cost improvement (corresponding to a 10.47% pipeline cost savings). Table 46 provides the water flowrate breakdown and distribution attained within the various merged pipeline segments and branches for Cases 1 and 2. Likewise, Table 47 provides the flowrate breakdown and distribution for Cases 3 and 4. Tables 48 and 49 outline all length and diameters details attained for Case 1 and 2 designs, respectively. Tables 50 and 51 outline the same information in terms of length and diameters details attained for Case 3 and 4 designs, respectively. Tables 47-50 also indicate the branching features associated with each design, as all merged pipeline segments, common node junctions, and the number of branching levels attained are also presented.

Table 46. Summary of flowrate distribution obtained for forward branching scenarios (Cases 1and 2)

Flow	**(t/h)**		**(t/h)**		**(t/h)**		**(t/h)**		**(t/h)**	
P1S1	100.00	N	0	N	0					P1D1
		N		N	0					P1D2
		N		N	100.00					DTR-P1
		N		N		N	0	N	0	P3D1
		N	100	N	0	N		N	0	CTRD
		N		N		N	0	N	0	WASTE
		N		N		N		N	0	P4D1

Table 46. Continued

Flow	(t/h)		(t/h)		(t/h)		(t/h)		(t/h)	
		N	59.49							DTR-P2
		N		N	0					P1D2
P2S1		N		N		N	0			P1D1
	70.0	N	10.506	N		N	10.51	N	0	CTRD
		N		N	10.51	N		N	10.51	P3D1
		N		N		N	0	N	0	WASTE
		N		N		N		N	0	P4D1
		N	0	N	0					P1D1
		N		N	0					P1D2
P2S2		N		N	150.31					DTR-P2
	160.00	N		N		N	0	N	0	CTRD
		N	160	N	9.69	N		N	0	P3D1
		N		N		N	9.69	N	0	WASTE
		N		N		N		N	9.69	P4D1
		N		N	8.94					P4D1
		N	124.49	N	115.56	N	115.56			DTR-P4
P4S1		N		N		N	0			WASTE
	130.00	N		N	0	N	0			P1D1
		N	5.50	N		N	0			P1D2
		N		N	5.51	N	5.51			P3D1
		N		N		N	0			CTRD
		N	100	N	100.00					P1D1
STR-P1		N		N	0					P1D2
	100.00	N		N	0					P3D1
		N	0	N	0	N	0			P4D1
		N		N		N	0			WASTE
		N	84.71							P1D2
STR-P2		N		N	41.32					P1D1
	209.80	N	125.09	N	28.08					P3D1
		N		N	55.69	N	55.69			P4D1
		N		N		N	0			WASTE
		N	9.09							P3D1
STR-P4		N		N	35.687	N	35.68			P4D1
	115.56	N	106.47	N		N	0			WASTE
		N		N	70.783	N	21.41			P1D1
		N		N		N	49.36			P1D2
		N	0							P4D1
FRESH		N		N	36.816					P3D1
	70.00	N	70.00	N	33.184	N	17.26			P1D1
		N		N		N	15.92			P1D2

Table 47. Summary of flowrate distribution obtained for backward branching scenarios (Cases 3and 4)

Flow	**(t/h)**		**(t/h)**		**(t/h)**		**(t/h)**		**(t/h)**		**(t/h)**		**(t/h)**	
		N	0											P2S2
		N		N	0									P1S1
		N		N		N	100							STR-P1
		N		N		N		N	0					P4S1
P1D1	180	N	180	N		N		N		N	41.32	N	41	STR-P2
		N		N	180	N	80	N		N		N	0	P2S1
		N		N		N		N	80	N	17.26			FRESH
		N		N		N		N		N	21.41	N	21	STR-P4
		N		N		N		N		N		N	0	CTRS
		N		N	0									P2S2
		N	84.71	N	84.71	N	84.71							STR-P2
		N		N		N	0							P2S1
		N		N	0									P1S1
P1D2	150	N		N		N	0							STR-P1
		N	65.28	N		N		N	0					P4S1
		N		N	65.28	N	65.28	N		N	15.92			FRESH
		N		N		N		N	65.28	N	49.36	N	49	STR-P4
		N		N		N		N		N		N	0	CTRS
	36.816													FRESH
		N		N	0									CTRS
		N	14.59	N	14.59	N	9.08							STR-P4
P3D1		N		N		N	5.50							P4S1
	53.18	N		N		N	28.08							STR-P2
		N		N	38.58	N	10.50	N	10.50					P2S1
		N	38.58	N		N		N	0					P2S2
		N		N	0	N	0							STR-P1
		N		N		N	0							P1S1
		N	8.935											P4S1
		N		N	0	N	0							STR-P1
		N		N		N	0							P1S1
P4D1		N		N		N		N	55.68					STR-P2
	110	N	101.06	N		N	65.37	N	9.69	N	0			P2S1
		N		N	101.06	N		N		N	9.69			P2S2
		N		N		N		N	35.68					STR-P4
		N		N		N	35.68	N	0	N	0			CTRS
		N		N		N		N		N	0			FRESH
DTR-P1	100													P1S1
DTR-P2	209.80	N	59.4											P2S1
		N	150.3											P2S2
DTR-P4	115.55													P4S1

Table 48. Pipeline length and diameter segments obtained for forward branching scenario, Case 1

(m)	L	D		L	D		L	D		L	D		L	D	
P1S1	1.4	0.2	N	0.8	0	N	0.8	0							P1D1
			N			N	1.8	0							P1D2
			N	0.6	0.2	N	0.6	0.2							DTR-P1
			N			N	2	0	N	0.8	0	N	2.8	0	P3D1
			N			N			N			N	0.6	0	CTRD
			N			N			N	5.4	0	N	5.8	0	WASTE
			N			N			N			N	2.2	0	P4D1
P2S1	1.2	0.2	N	0.4	0.2										DTR-P2
			N	1.2	0.1	N	5.6	0							P1D2
			N			N	1	0.1	N	4.4	0				P1D1
			N			N			N	0.6	0.1	N	0.6	0	CTRD
			N			N			N			N	2.8	0.1	P3D1
			N			N			N	5.6	0	N	5.8	0	WASTE
			N			N			N			N	2.2	0	P4D1
P2S2	0.6	0.3	N	6.6	0	N	1.2	0							P1D1
			N			N	1.4	0							P1D2
			N	1.6	0.3	N	0.4	0.3							DTR-P2
			N			N	2.2	0.1	N	0.6	0	N	0.6	0	CTRD
			N			N			N			N	2.8	0	P3D1
			N			N			N	5.6	0.1	N	5.8	0	WASTE
			N			N			N			N	2.2	0.1	P4D1
P4S1	0.4	0.2	N	0.6	0.2	N	0.6	0.1							P4D1
			N			N	0.8	0.2	N	0.8	0.2				DTR-P4
			N			N			N	3.4	0				WASTE
			N	4.4	0.1	N	5.4	0	N	0.8	0				P1D1
			N			N			N	1.8	0				P1D2
			N			N	0.2	0.1	N	4.2	0.1				P3D1
			N			N			N	3.2	0				CTRD
STR-P1	0.4	0.2	N	2.8	0.2	N	0.8	0.2							P1D1
			N			N	1.8	0							P1D2
			N	0.6	0	N	3.6	0							P3D1
			N			N	5.4	0	N	2.2	0				P4D1
			N			N			N	5.8	0				WASTE
STR-P2	1	0.3	N	5.6	0.2										P1D2
			N	1	0.2	N	4.4	0.2							P1D1
			N			N	3.4	0.2							P3D1
			N			N	5.6	0.2	N	2.2	0.2				P4D1
			N			N			N	5.8	0				WASTE

Table 48. Continued

(m)	L	D		L	D		L	D		L	D		L	D	
STR-P4	1.6	0.2	N	4	0.1										P3D1
			N	0.2	0.2	N	3.6	0.2	N	2.2	0.2				P4D1
			N			N			N	5.8	0				WASTE
			N			N	5.6	0.2	N	0.8	0.1				P1D1
			N			N			N	1.8	0.2				P1D2
FRESH	6.2	0.2	N	8	0										P4D1
			N	0.6	0.2	N	1.4	0.2							P3D1
			N			N	7.2	0.2	N	0.8	0.1				P1D1
			N			N			N	1.8	0.1				P1D2

Table 49. Pipeline length and diameter segments obtained for forward branching scenario, Case 2

(m)	L	D		L	D		L	D		L	D		L	D	
P1S1	1.1	0.2	N	0.8	0	N	0.88	0							P1D1
			N			N	1.88	0							P1D2
			N	0.48	0.2	N	0.68	0.2							DTR-P1
			N			N	1.76	0	N	0.8	0	N	2.8	0	P3D1
			N			N			N			N	0.7	0	CTRD
			N			N			N	5	0	N	5.9	0	WASTE
			N			N			N			N	2	0	P4D1
P2S1	1.1	0.2	N	0.4	0.2										DTR-P2
			N	1	0.1	N	5.32	0							P1D2
			N			N	0.88	0.1	N	4	0				P1D1
			N			N			N	0.5	0.1	N	0.7	0	CTRD
			N			N			N			N	2.8	0.1	P3D1
			N			N			N	5.4	0	N	5.9	0	WASTE
			N			N			N			N	2	0	P4D1
P2S2	0.4	0.3	N	6.24	0	N	1.28	0							P1D1
			N			N	1.48	0							P1D2
			N	1.48	0.3	N	0.48	0.3							DTR-P2
			N			N	2.08	0.1	N	0.5	0	N	0.7	0	CTRD
			N			N			N			N	2.8	0	P3D1
			N			N			N	5.4	0.1	N	5.9	0	WASTE
			N			N			N			N	2	0.1	P4D1

Table 49. Continued

(m)	L	D		L	D		L	D		L	D	L	D	
P4S1	0.2	0.2	N	0.48	0.2	N	0.56	0.1						P4D1
			N			N	0.68	0.2	N	0.8	0.2			DTR-P4
			N			N			N	3.5	0			WASTE
			N	4.04	0.1	N	4.8	0	N	0.9	0			P1D1
			N			N			N	1.9	0			P1D2
			N			N	0.2	0.1	N	4.2	0.1			P3D1
			N			N			N	3	0			CTRD
STR-P1	0.2	0.2	N	2.44	0.2	N	0.88	0.2						P1D1
			N			N	1.88	0						P1D2
			N	0.6	0	N	3.56	0						P3D1
			N			N	5.04	0	N	2	0			P4D1
			N			N			N	5.9	0			WASTE
STR-P2	0.7	0.3	N	5.32	0.2									P1D2
			N	0.88	0.2	N	4.2	0.2						P1D1
			N			N	3.24	0.2						P3D1
			N			N	5.36	0.2	N	2	0.2			P4D1
			N			N			N	5.9	0			WASTE
STR-P4	1.3	0.2	N	3.84	0.1									P3D1
			N	0.28	0.2	N	3.28	0.2	N	2	0.2			P4D1
			N			N			N	5.9	0			WASTE
			N			N	4.92	0.2	N	0.9	0.1			P1D1
			N			N			N	1.9	0.2			P1D2
FRESH	5.5		N	7.92	0									P4D1
		0.2	N	0.48		N	1.36	0.2						P3D1
			N		0.2	N	6.6	0.2	N	0.8	0.1			P1D1
			N			N			N	1.8	0.1			P1D2

Table 50. Pipeline length and diameter segments obtained for backward branching scenario, Case 3

	L(m)	D(m)		L(m)	D(m)		L(m)	D(m)		L(m)	D(m)		L(m)	D(m)		L(m)	D(m)		L(m)	D(m)	
	0.8	0.3	N	7.6	0																P2S2
			N	0.8	0.3	N	1.4	0													P1S1
			N			N	2	0.3	N	0.4	0.2										STR-P1
P1D1			N			N			N	0.6	0.2	N	6.8	0							P4S1
			N			N			N			N	0.2	0.2	N	1.4	0.2	N	0.6	0.2	STR-P2
			N			N			N			N			N			N	2	0	P2S1
			N			N			N			N			N	10	0.1				FRESH
			N			N			N			N			N	2.2	0.1	N	1.6	0.1	STR-P4
			N			N			N			N			N			N	1.6	0	CTRS
	1.4	0.3	N	2.8	0.2	N	4.4	0													P2S2
			N			N	1.8	0.2	N	0.6	0.2										STR-P2
			N			N			N	2	0										P2S1
P1D2			N	1.2	0.2	N	1.4	0													P1S1
			N			N	2	0.2	N	0.4	0										STR-P1
			N			N			N	0.6	0.2	N	6.8	0							P4S1
			N			N			N			N	0.2	0.2	N	10	0.1				FRESH
			N			N			N			N			N	2.2	0.2	N	1.6	0.2	STR-P4
			N			N			N			N			N			N	1.6	0	CTRS
	8.2	0.2																			FRESH
	0.8	0.2	N	0.8	0.1	N	0.8	0													CTRS
			N			N	2.4	0.1	N	1.6	0.1										STR-P4
P3D1			N			N			N	5.2	0.1										P4S1
			N	2.6	0.2	N	1.4	0.2	N	0.6	0.2										STR-P2
			N			N			N	1.4	0.1	N	0.6	0.1							P2S1
			N			N			N			N	1.6	0							P2S2
			N			N	0.8	0	N	0.4	0										STR-P1
			N			N			N	3.4	0										P1S1
	1.2	0.2	N	0.4	0.1																P4S1
			N	4.4	0.2	N	2.6	0	N	0.4	0										STR-P1
			N			N			N	3.4	0										P1S1
P4D1			N			N	0.2	0.2	N	3.4	0.2	N	0.6	0.2							STR-P2
			N			N			N			N	1.4	0.1	N	0.6	0				P2S1
			N			N			N			N			N	1.6	0.1				P2S2
			N			N			N	0.2	0.2	N	1.6	0.2							STR-P4
			N			N			N			N	1	0	N	0.6	0				CTRS
			N			N			N			N			N	7.2	0				FRESH
DTR-P1	2.6	0.2																			P1S1
DTR-P2	1.0	0.3	N	0.6	0.2																P2S1
			N	1.6	0.3																P2S2
DTR-P4	2.6	0.2			0																P4S1

Table 51. Summary of flowrate distribution obtained for backward branching scenario, Case 4

	L(m)	**D(m)**		**L(m)**	**D(m)**		**L(m)**	**D(m)**		**L(m)**	**D(m)**		**L(m)**	**D(m)**		**L(m)**	**D(m)**		**L(m)**	**D(m)**	
P1D1	0.6	0.3	N	7.1	0																P2S2
			N	0.7	0.3	N	1.5	0													P1S1
			N			N	1.8	0.3	N	0.5	0.2										STR-P1
			N			N			N	0.5	0.2	N	6.4	0							P4S1
			N			N			N			N	0.2	0.2	N	1.2	0.2	N	0.68	0.2	STR-P2
			N			N			N			N			N			N	1.68	0	P2S1
			N			N			N			N			N	9.8	0.1				FRESH
			N			N			N			N			N	1.9	0.1	N	1.76	0.1	STR-P4
			N			N			N			N			N			N	1.76	0	CTRS
P1D2	1.2	0.3	N	2.6	0.2	N	4.4	0													P2S2
			N			N	1.6	0.2	N	0.7	0.2										STR-P2
			N			N			N	1.7	0										P2S1
			N	1.1	0.2	N	1.5	0													P1S1
			N			N	1.8	0.2	N	0.5	0										STR-P1
			N			N			N	0.5	0.2	N	6.4	0							P4S1
			N			N			N			N	0.2	0.2	N	9.8	0.1				FRESH
			N			N			N			N			N	1.9	0.2	N	1.76	0.2	STR-P4
			N			N			N			N			N			N	1.76	0	CTRS
P3D1	7.4	0.2																			FRESH
	0.6	0.2	N	0.9	0.1	N	0.7	0													CTRS
			N			N	2.3	0.1	N	1.6	0.1										STR-P4
			N			N			N	5	0.1										P4S1
			N	2.4	0.2	N	1.2	0.2	N	0.7	0.2										STR-P2
			N			N			N	1.4	0.1	N	0.7	0.1							P2S1
			N			N			N			N	1.7	0							P2S2
			N			N	0.8	0	N	0.6	0										STR-P1
			N			N			N	3.1	0										P1S1
P4D1	0.8	0.2	N	0.5	0.1																P4S1
			N	4.2	0.2	N	2.4	0	N	0.4	0										STR-P1
			N			N			N	3.1	0										P1S1
			N			N	0.2	0.2	N	3.1	0.2	N	0.7	0.2							STR-P2
			N			N			N			N	1.4	0.1	N	0.7	0				P2S1
			N			N			N			N			N	1.7	0.1				P2S2
			N			N			N	0.2	0.2	N	1.6	0.2							STR-P4
			N			N			N			N	1	0	N	0.7	0				CTRS
			N			N			N			N			N	6.9	0				FRESH
DTR-P1	2.2	0.2																			P1S1
DTR-P2	0.7	0.3	N	0.7	0.2																P2S1
			N	1.7	0.3																P2S2

V.5. Conclusions

In this work, additional considerations that account for pipeline merging scenarios have been studied for wastewater regeneration and reuse networks. The proposed framework allows cost-effective interplant water reuse and treatment network designs to be identified, by implementing a systematic approach for interplant water network synthesis and design that account for pipeline merging. An artificial case study has been implemented, and a number of centralized and decentralized wastewater treatment options were incorporated. . In addition to the improved design-screening ability of less complex pipeline networks, merging together common pipe segments that carry similar water qualities was observed to achieve various cost-enhancements in the overall design of the system.

CHAPTER VI

SUMMARY

In this work, several methods that assist in the design of interplant water networks for industrial water and wastewater management strategies have been introduced. Methods that involve accounting for interplant spatial aspects, as well as interconnectivity considerations within wastewater reuse and regeneration networks, have been studied. Each of the proposed frameworks allow cost-effective interplant water reuse and treatment network designs to be identified, by implementing a systematic design approach for interplant water network synthesis. Several case studies have been implemented to demonstrate each of the proposed methods, by assuming a spatial layout for the city, as well as by incorporating locations for a number of water-consuming and wastewater producing processes. Moreover, the potential options for using centralized and decentralized wastewater treatment facilities were also incorporated, in the course of determining wastewater regeneration and reuse networks. The results indicate very attractive wastewater treatment and reuse schemes for the water network designs extracted. Moreover, cost-efficient water networks that involve merged pipeline segments in the overall design were also identified.

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