ISSN 2347 - 3983
Volume 6, No.7 July 2018
International Journal of Emerging Trends in Engineering Research
Available Online at http://www.warse.org/IJETER/static/pdf/file/ijeter01672018.pdf
https://doi.org/10.30534/ijeter/2018/01672018

A Lagrangian Relaxation-based Algorithm to solve a Collaborative Water Supply Chain Network Design Problem

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ABSTRACT

Water supply and waste water collection system is a set of physical infrastructures designed to purify water, then, deliver it to demand centers, and finally collect the waste water. Besides, water shortage is one of the major threats for whole of the world. So, operational managing of water supply and waste water collection networks and also designing an efficient supply chain network for such systems are so important and strategic. In this regard, this study proposes a new mathematical formulation for a collaborative water supply chain network design problem. The proposed model aims to optimize the total cost of such system as the economic factors including establishing, collecting, processing, and distributing as well as transition costs. To solve the proposed mixed integer linear programming model, a heuristic algorithm upon Lagrangian relaxation method has been utilized. The proposed algorithm finds feasible lower bound and optimal upper bound solutions, iteratively. Some numerical examples are considered to evaluate the efficiency of proposed model as well as the performance of solution method to find an optimal solution for the problem especially by increasing the size of model.

Keywords -Water supply chain, waste water collection system, Lagrangian relaxation method, heuristic;

I. INTRODUCTION

Supply Chain (SC) systems have been studied to facilitate the transforming of products between different levels and echelons of SC *i.e*. manufacturers, retailers and costumers [1-3]. In recent decade, by developing the recycling and remanufacturing technologies, the researchers paid more attentions to reverse logistic in a supply chain network [4]. The last decade has seen a rapid development of decision-making models for reverse flows of supply chain network [5-7]. Accordingly, designing a collaborative supply chain network i.e. water supply chain has been motivated by both academia and supply chain practitioners to perform a robust plan in this regard [8-9].

The literature of water supply chain is so novel and there is a few works in the last decade [10-12]. For instance, Elala *et al*. [13] explored the water quality in water supply chain by considering a real case study. Using operation research models to simulate the water supply chain is an efficient way to probe such systems. In this regard, Saif and Almansoori [14] proposed a mixed integer linear programming model to design a water desalination supply chain. Their majority decisions in their mode were the optimal locations of facilities and capacity expansions of water desalination supply chain. Furthermore, Gao and You [15] considered a mixed integer linear fractional programming model for water supply chain. The objective of their model aims to maximize the freshwater consumption by assuming the economic concepts of such system. In another similar study, they proposed a mixed integer non-linear programming model to get a better economic and life cycle performance [16]. The proposed model was covered the wire life cycle of electricity generated from shale gas in a wastewater collection system. Recently, considering uncertainty of parameters and decision variables of water supply chain is attended by several studies. In this way, Medina-González *et al.* [17] developed a framework for optimal design of a decentralized water supply chain. Their formulation is based on a competitive leader-follower game in which the leader should propose a set of negotiation contracts and, at the same time, predict the follower response (to accept/reject the contract) is proposed. The impact of the follower design decisions over the leader objective is evaluated by fixing the establishment costs of facilities. Whole of them was considered by a scenario-based dynamic formulation. Recently, Ghelichi *et al.* [18] proposed a robust optimization model to design a water distribution system under uncertainty by a multi-period mixed integer linear programming model. To validate the propose formulation a real case study in Mashhad, Iran was presented.

The integration of water supply system with wastewater collection system prevents the suboptimal designs resulted from separately considering the economic factors e.g. establishing, processing, distributing, collecting and transition costs [10]. Due to systemic and special structure of water supply chain as well as strategic long-term planning horizon of water supply and wastewater collection system (WSWCS) design problems, this study proposes a new decision-making model to achieve this end. WSWCS design problems typically include decisions about the establishment of water and wastewater treatment centers, the installation of pipelines, the construction of pump stations, the establishment of tanks, and the determination of capacities. All of the offered mentioned decisions can be modeled as integer decision variables. In addition, it is incumbent upon these problems to determine the recharges between facilities by modeling them as continuous decision variables. Therefore, most of WSWCS design mathematical models are in types of mixed-integer programming models. The lagrangian relaxation method [19] is a resolution strategy which has been deployed appropriately in the field of complex mixed-integer programming problems like transition problems e.g. [8] scheduling problems e.g. [20], supply chain network design problems e.g. [10] and network planning problems e.g. [21].

The rest of the paper is organized as follows. The proposed model for WSWCS network is formulated in Section II. Section III presents the considered heuristic algorithm along with its steps with details. Computational experiments, comparison, and some analyses are reported in section IV. Finally, Section V provides concluding remarks and directions for further research.

II. PROBLEM FORMULATION

This paper considers a multi-level WSWCS including treatment center, domestic zone, wastewater treatment center, agricultural zone, ground water. Fig. 1 shows the graphical presentation of considered WSWCS. In the first level of WSWCS, dams, water treatment centers, waste-water treatment centers, recharge facilities and conveyance networks constitute primary components of the concerned WSWCS. WSWCS design models typically ought to determine capacities, configurations, and operating policies of such components in order to meet two sorts of demands, i.e. domestic and agricultural demands. Surface waters, i.e. upstream rivers and reservoirs, as well as the groundwater aquifer provide domestic water supplies. Mountain front recharges, rainfalls and precipitations on the upstream watershed contribute to the upstream rivers' flow. The surface water, either is reserved in dams or directly is taken from upstream rivers, must be treated at water treatment centers to meet the requirements of potable uses. A percentage of precipitation on the basin area is abstracted to depression, also an amount of it evaporates or constitutes to the natural runoffs, but the rest of it, recharges the aquifer. Precipitation on the basin area can also satisfy apart of agricultural demands. Also, there is water infiltration to the aquifer from domestic and agricultural zones. The wastewater produced in domestic areas, can be collected and conveyed to wastewater treatment centers.

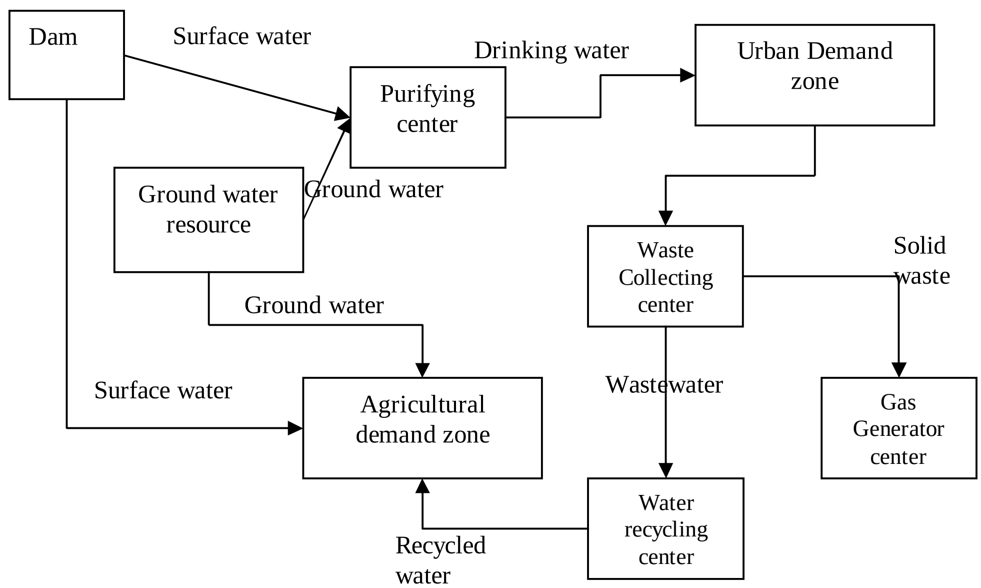

Fig. 1. The structure of proposed water supply chain network

A. Assumptions

The following assumptions are considered for the problem formulation:

- Satisfaction of water users' demands.
- Satisfaction of flow conservation through nodes.
- Meeting capacity constraints for water and wastewater treatment centers.
- Limiting canal/pipeline flows by their maximum canal/pipeline capacity.
- Logical constraints related to the different capacity levels for water and wastewater treatment centers, pipelines and canals.
- Meeting the required downstream river flows.
- Meeting the required groundwater storage.

B. Notations and Formulations

The model is based on the following notations as follows:

Indices:

i Indices of rivers

m Indices of dams

j Indices of potential water treatment centers,

l Indices of demand zones, including both domestic and agricultural zones

n Indices of potential wastewater treatment centers

Parameters:

TC_{im} Transition cost per unit form upstream river i and dam m

TC_{ij} Transition cost per unit from upstream river i and water treatment center j

TC_{jl} Transition cost per unit from water treatment center j to domestic zone l

$TC_{\ln}$ Transition cost per unit form domestic zone l to wastewater treatment center n

TC_{nl} Transition cost per unit form wastewater treatment center n to agricultural zone l

TC_{mj}	Transition cost per unit form dam zone *m* to water treatment center *j*
TC_{ni}	Transition cost per unit from wastewater treatment center *n* to downstream river *i*
FC_j	Fixed opening cost of water treatment center *j* to be established
FC_n	Fixed opening cost of wastewater treatment center *n* to be established
MC_m	Variable cost of controlling collected water per unit from dam *m*
MC_j	Variable cost of collected water per unit from water treatment center *j*
MC_n	Variable cost of processing wastewater per unit wastewater treatment center *n*
PC_m	Cost of purchasing collected dam water from dam *m*
PC_j	Cost of purchasing processed water from water treatment center *j*
PC_n	Cost of purchasing processed wastewater from wastewater treatment center *n*
MAX_j	Maximum desired number of established sites for water treatment centers
MAX_n	Maximum desired number of established sites for wastewater treatment centers
Ad_l	Demand of agricultural zone *l* for waste water
Dd_l	Fraction of domestic zone for collected water
CAP_i	Capacity of river *i*
CAP_m	Capacity of dam *m*
CAP_j	Capacity of water treatment center *j*
CAP_n	Capacity of wastewater treatment center *n*

Decision variables:

X_{im}	Amount of water flow between upstream water *i* and dam *m*
X_{ij}	Amount of water flow between upstream water *i* and water treatment center *j*
X_{mj}	Amount of water flow between dam *m* and water treatment center *j*
X_{jl}	Amount of water transformed between water treatment center *j* and domestic zone *l*
$X_{\ln}$	Amount of returned water from domestic zone *l* transformed to wastewater treatment center *n*
X_{nl}	Amount of retuned wastewater from wastewater treatment center transformed agricultural zone *l*
X_{ni}	Amount of water flow between wastewater treatment center *n* and downstream river *i*
Y_j	1 if water treatment center *j* is to be established, otherwise 0
Y_n	1 if wastewater treatment center *n* is to be established, otherwise 0

The proposed mixed integer linear programming model of WSWCS problem is as follows:

$$min\ Z = Z_{FC} + Z_{VC} + Z_{TC} + Z_{PC} \quad (1)$$

$$Z_{FC} = \sum_{j=1}^{J} FC_j \times Y_j + \sum_{n=1}^{N} FC_n \times Y_n \quad (2)$$

$$Z_{VC} = \sum_{m=1}^{M} MC_m (\sum_{j=1}^{J} X_{mj}) + \sum_{j=1}^{J} MC_j (\sum_{l=1}^{L} X_{jl}) + \sum_{n=1}^{N} MC_n (\sum_{l=1}^{L} X_{nl})) \quad (3)$$

$$Z_{TC} = \sum_{i=1}^{I}\sum_{m=1}^{M} TC_{im} \times X_{im} + \sum_{m=1}^{M}\sum_{j=1}^{J} TC_{mj} \times X_{mj} + \sum_{j=1}^{J}\sum_{l=1}^{L} TC_{jl} \times X_{jl} \quad (4)$$

$$+ \sum_{l=1}^{L}\sum_{n=1}^{N} TC_{\ln} \times X_{\ln} + \sum_{l=1}^{L}\sum_{n=1}^{N} TC_{nl} \times X_{nl} + \sum_{n=1}^{N}\sum_{i=1}^{I} TC_{ni} \times X_{ni} + \sum_{i=1}^{I}\sum_{j=1}^{J} TC_{ij} \times X_{ij}$$

$$Z_{PC} = \sum_{m=1}^{M} PC_m \times (\sum_{j=1}^{J} X_{mj}) + \sum_{j=1}^{J} PC_j \times (\sum_{l=1}^{L} X_{jl}) + \sum_{n=1}^{N} PC_r \quad (5)$$

Such that, following constraints are to specify the flow of water in the proposed WSWCS between the facilities. For instance, equation (8) and (9) shows the amount of processed water from water treatment center and wastewater treatment center should be met the demand of domestic and agricultural zones, respectively.

$$\sum_{i=1}^{I} (X_{im} + X_{ij}) = \sum_{l=1}^{L} X_{jl}, \forall m, j \quad (6)$$

$$\sum_{m=1}^{M} X_{mj} + \sum_{i=1}^{I} X_{ij} = \sum_{l=1}^{L} X_{jl}, \forall j \quad (7)$$

$$\sum_{j=1}^{J} X_{jl} = Dd_l, \forall l \quad (8)$$

$$\sum_{n=1}^{N} X_{nl} = Ad_l, \forall l \quad (9)$$

$$\sum_{l=1}^{L} X_{\ln} = \sum_{l=1}^{L} X_{nl} + \sum_{i=1}^{I} X_{ni}, \forall n \quad (10)$$

Notably, the capacity of facilities is limited by the predefined size for upstream river and dam as illustrated in equation (11) and (12), respectively. In addition, the flow of proceed water through a facility e.g. water treatment centers and wastewater treatment centers is allowed only the respective facility is open and has enough capacity as well according to equation (13) and (14).

$$\sum_{m=1}^{M} X_{im} + \sum_{j=1}^{J} X_{ij} \le CAP_i, \forall i \quad (11)$$

$$\sum_{j=1}^{J} X_{mj} \le CAP_m, \forall m \quad (12)$$

$$\sum_{l=1}^{L} X_{jl} \le CAP_j \times Y_j, \forall j \quad (13)$$

$$\sum_{l=1}^{L} X_{\ln} \le CAP_n \times Y_n, \forall n \quad (14)$$

Furthermore, the number of facilities in each echelon including of water treatment centers and wastewater treatment centers is limited by a predefined maximum number.

$$\sum_{j=1}^{J} Y_j \le MAX_j \quad (15)$$

$$\sum_{n=1}^{N} Y_n \le MAX_n \quad (16)$$

Finally, the decision variables are guaranteed.

$$Y_j, Y_n \in \{0,1\}$$

$$X_{im}, X_{mj}, X_{ij}, X_{\ln}, X_{nl}, X_{ni} \ge 0$$

III. SOLUTION APPROACH

Since solving the proposed problem by exact solver e.g. GAMS gets too much time despite of all variables and constraints. This study uses a heuristic algorithm based on Lagrangian relaxation methodology to solve the model in a reasonable time. The algorithm includes two main parts. First, the problem is relaxed by removing some sets of constraints from the formulation and adding them to the objective function after multiplying them with Lagrange multipliers. Second, by utilizing the solution of the relaxed problem, a feasible solution is obtained. This feasible solution gives an upper bound for the original problem. By using these two components, the subgradient algorithm tries to strengthen the lower and upper bounds in order to fill the gap between them and reach the optimal solution [22].

In a nutshell, the steps of the proposed algorithm can be considered as follows:

Step 0: Choose an initial Lagrange multiplier π_t and set $t = 0$.

Step 1: Let $\pi = \pi_t$ and solve the relaxed problem with the optimal value $Z_{(\pi)}$ and update the lower bound as follows:

$$LB = \max\{LB, Z_{(\pi)}\} \tag{17}$$

Step 2: Given the locations of facilities and then their allocations from the relaxed problem, solve the restricted with $Z_{(\pi)}$. If the restricted problem yield an infeasible solution, the number of fixed locations obtained from the relaxed problem is decreased until the restricted problem makes a feasible solution. Then, the upper bound is updated as follows:

$$UB = \min\{UB, Z_{(\pi)}\} \tag{18}$$

Step 3: Update the Lagrange multipliers as follows:

$$\pi_{t+1} = \max(\pi_t + \mu_t \times f(x), 0) \tag{19}$$

Where $\mu_t = w.\dfrac{UB - Z_{(\pi)}}{\|f(x)\|}$ and being w is a stochastic number between 0 and 2 that is decreased after a certain number of iterations without improvement.

Step 4: $t = t + 1$

Step 5: if the stopping condition is not satisfied, go to Step 1. Otherwise, output the best lower bound for the problem.

IV. EXPERIMENTAL RESULTS

In this section, by fifteen numerical examples, the model is solved and then analyzed to probe its efficiency as well as the performance of considered solution methodology. The test problems are generated randomly by an approach benchmarked from [3-5]. Table I shows the instances for the fifteen random problems in three levels i.e. small, medium and large sizes. In addition, the distribution of parameters is satisfied in Table II. Finally, the results of our experiments are given by Table II. It should be noted that all results were obtained on a Laptop with processor Core 2 Duo-2.26 GHz and 2 GB of RAM [23], [24].

TABLE I
INSTANCES FOR TEST PROBLEMS

The levels of problem	Number of problem (P_i)	Size of problems (I, M, J, L, N)
Small	P1	(1, 5, 10, 9, 4)
	P2	(2, 8, 12, 13, 5)
	P3	(4, 12, 16, 15, 8)
	P4	(7, 16, 15, 16, 11)
	P5	(9, 14, 17, 19, 14)
Medium	P6	(14, 32, 33, 35, 23)
	P7	(17, 35, 34, 37, 25)
	P8	(21, 37, 36, 39, 27)
	P9	(25, 39, 38, 41, 29)
	P10	(31, 37, 36, 39, 27)
Large	P11	(47, 55, 59, 111, 36)
	P12	(51, 57, 61, 115, 37)
	P13	(55, 59 , 63, 119, 39)
	P14	(59, 61, 65, 123, 40)
	P15	(63, 63 , 67, 127, 42)

TABLE II
PARAMETERS AND THEIR TURFACES

Parameters	Surfaces
PC_m, PC_j, PC_n	$rand\{5.6,\ldots,10\}$
MC_m, MC_j, MC_n	$rand\{2, 3,\ldots,5\}$
TC	$rand\{1.2,\ldots,6\}$
Dd_l, Ad_l	$rand\{16,17,\ldots 24\}$

TABLE III
RESULTS OF ALGORITHMS (CPU IN SECOND)

Test problem	*Proposed heuristic algorithm*		*Exact solver*		
	LB	*CPU*	*Output*	*CPU*	*Gap*
P1	4922	*87.21*	**4922**	*154.28*	0
P2	13274	*105.82*	**13171**	*398.17*	0.0078
P3	40847	130.15	**40604**	*899.56*	0.0059
P4	136494	147.02	**136113**	*2043.7*	0.002
P5	1100042	166.36	**1098560**	*6864.49*	0.001
P6	1990244	168.09	-	-	-
P7	5538195	169.60	-	-	-
P8	10245400	175.2995	-	-	-
P9	17745188	175.447	-	-	-
P10	28992827	200.2247	-	-	-
P11	31198843	201.8644	-	-	-
P12	33037825	228.5734	-	-	-
P13	43093175	248.5379	-	-	-
P14	75894370	250.2172	-	-	-
P15	17745188	275.1564	-	-	-

V. CONCLUSION AND FUTURE WORKS

In this study, a new mathematical formulation for water supply and wastewater collection system (WSWCS) was proposed. The motivation of problem and its literature review were conducted in the first section. The problem description and mathematical formulation were addressed clearly in the second section. In addition, the solution approach as the main innovation of this study was proposed in the third section. Finally, the obtained LBs of algorithm were validated by an exact solver and it was analyzed with some numerical test problems. Results showed the efficiency of considered mathematical model and the performance of solution methodology based on Lagrangian relaxation structure.

To get the future directions of this study, more analyses on the developed model needs to be explored. In addition, the considered Lagrangian relaxation based heuristic algorithm should be analyzed more sensitively by modifying its steps and changing the input parameters. Moreover, the proposed model can be developed for future works by some other real constraints. The technology of water treatment centers and or wastewater treatment centers should be analyzed. Considering uncertainty of parameters and stochastic programming model can be ordered in future works.

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