Vol. 11, No. 1, 2024, Pages 1-18

JIEMS

Journal of Industrial Engineering and Management Studies

journal homepage: www.jiems.icms.ac.ir

A multi-objective mathematical model for virtual water allocation in the food industry of Khuzestan province using meta-heuristic algorithms

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Received: Dec 2023-17/ Revised: Apr 2024-08/ Accepted: Apr 2024-29

Abstract

The purpose of this research is to optimize the use of water resources in dams in Khuzestan province. For this purpose, we seek to optimize the cost and time of sending water to each of the cities from the total dams in Khuzestan province. Therefore, mixed integer linear programming (MILP) proposed and explained based on the pricing components of the water consumed in the food industry and its shipping cost, water supply sources of the province, government incentive policies, and free trade. Hence, the most important contribution of current research is the design of a MILP for the allocation of virtual water in the food industry of Khuzestan province in order to determine the role and position of virtual water trade in the management of water resources in the food sector of Khuzestan province. The model is solved using the deterministic epsilon constraint method and NSGA-II and MOPSO algorithms meta-heuristically. According to the results presented in this research, the water supply from the Balaroud dam to the cities of Ahvaz, Izeh, Abadan, Baghmolk, and Bandar Imam Khomeini has not been determined to be optimal. The same dam sends a certain amount of water to the cities of Andimeshk, Dezful, Shush, Shushtar and Gotvand. The results showed that NSGA-II has a more acceptable performance than the MOPSO algorithm from the point of view of three criteria, and the MOPSO algorithm has a better condition than the NSGA-II algorithm only in terms of the distance to the ideal point. In addition, according to the sensitivity analysis, it has been determined that the increase in water demand can increase the shipping time by 1.9% and the shipping cost by 60%. Therefore, the effect of water demand is more on time and not on cost. Increasing the budget can have an effect on cost and time, which of course has more effect on time than cost. The next parameter is the time interval between the cities and the production complex, which is expected to increase the water delivery time by 13%, which shows a relatively significant effect, while this effect on cost is less than on time.

Keywords: Water management of dams, Optimization, Epsilon constraint, Meta-heuristic algorithm

Paper Type: Original Research

1. Introduction

Water is one of the most fundamental elements of life. Having access to clean water for human needs is known as one of the basic factors and a factor of civilization so it has always been respected by societies, and different rivers across the world have been of great importance and sacred to the populations living in those areas. No country can maintain its economic, social, and political stability without ensuring that it has water, and without decreasing the amount of air pollution, the security of future generations in terms of water and food will be uncertain, and thus, sustainable development will remain just a catchy slogan. Today, the lack and pollution of water have seriously endangered the lives of millions of people living on earth, especially in poor countries. According to statistics, 80% of the world's population has access to only 20% of safe and sanitary water reserves. Diseases caused by contaminated water are also the cause of many deaths in the poor countries of the world (Heidari Kushalshah et al., 2023). Water is required for the manufacturing of any kind of goods and services. Water used in the manufacturing process of an agricultural or industrial product is called "virtual water". The term virtual water was first proposed by Allan in 1993. In this regard, an article presented by Professor Allan at the annual knowledge conference in London discussed the water scarcity in the Middle East and resource management to overcome the crisis. In the 1960s and 1970s, some research was conducted by the former Soviet Union to investigate the water balance

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in the world. In this research, the availability of water and its use has also been mentioned (Yeh et al., 2018). Today, many researchers, scientists, and scholars emphasize reviewing the policies and management approaches of water resources, so that the replacement approach proposed by them is the virtual water management approach. Virtual water is the sum of the total flow of water used to manufacture a product (Li et al., 2019). Virtual water, in other words, is the amount of water an industrial product or an agricultural product consumes during the production process to reach the final production stage, and its amount is equal to the sum of the total water consumed in the different stages of the production chain from the start to the end. A country or region can free itself from pressure on its water resources by choosing to be a virtual water importer. Climatic and cultural conditions, place of production, management, and planning are effective in the amount of virtual water of each product, and its amount is different for the same product in different regions. Virtual water trading can lead to the import of products from other regions. Thus, the negative effects of using water resources are avoided. In this way, the involvement of virtual water trade in trade policies causes a trade-off between the protection of water resources and food security (Wang et al., 2017). In comparison with the last two or three centuries, the world has entered a critical period in terms of preserving natural resources. Proper and appropriate management of existing natural resources is an important necessity to achieve sustainable development. Among all natural resources, fresh water is one of the main resources that should be given special importance. Due to the exploitation of their non-renewable fossil water to relieve the immediate pressure caused by water stress, many countries have caused the depletion of water reserves and resources, weakening economic development and reducing their long-term food security (Wu et al., 2019). Several researchers have argued that water-scarce regions can achieve high levels of global water use efficiency by importing products with high virtual water content and exporting products with very low virtual water content (Zhou et al., 2020). Virtual water, along with indigenous or local water, makes it possible to respond to water needs at the national level. This forms the concept of virtual water exchange. Accordingly, the importing countries, in addition to the goods, also receive the water used to manufacture those products. Thus, the water required for the manufacturing of these products from domestic sources is saved. Virtual water exchange within countries, between countries, and even continents can be used as a tool to improve the efficiency of water consumption at the global level, achieve water security in water-poor areas, and eliminate environmental limitations by determining suitable locations for production (Heydari Kushalshah et al., 2023). By taking into account the volume of virtual water contained in food imports in water-deficient countries, a close relationship between the availability of water and dependence on food imports is revealed. Therefore, food imports can be considered as one of the strong indicators in determining the level of water scarcity in countries (Yeh et al., 2018). Virtual water trading is not a new phenomenon, and simultaneously with the formation of markets and the expansion of exchanges between human societies, this type of trade also expanded in the form of exchanges of agricultural products. Nevertheless, the concept of virtual water and its trading has entered scientific discussions and national and international policies of water resources management and development in the last few years. In recent years, with the sharp increase in the world's population and the water stress in many countries, this tool has been proposed as one of the effective solutions for providing water and food security for different communities, especially in areas facing water scarcity. Wichelns (2001) investigated the role of virtual water in providing food security in different countries with an emphasis on Egypt and stated that the issue of the opportunity cost of water consumption is also one of the key components concerning the expansion of the concept of virtual water and its trades, which should be taken into consideration in an effective and optimal allocation of available water resources. Given the importance of the topic, it is tried to briefly investigate the concept of virtual water, virtual water trade, virtual water allocation, and food security of human societies in this paper (Wong et al., 2017). Considering that the main concern of the most important food industries and companies is to provide food security and allocate virtual water optimally. Given the need and necessity of allocating virtual water in the conditions of climatic fluctuations in Iran's food industry to create nutrition security, this research—as a case study—investigates the food industry of Khuzestan province and designs a model for allocating virtual water. Therefore, introducing and proposing a solution to virtual water allocation appears to be essential and necessary. The mathematical model proposed in this research can be determined and explained based on the pricing components of the water consumed in the food industry and its shipping cost, water supply sources of the province, government incentive policies, and free trade. Hence, the most important contribution of this research is the design of a mathematical model for the allocation of virtual water in the food industry of Khuzestan province in order to determine the role and position of virtual water trade in the management of water resources in the food sector of Khuzestan province. In this case, it is possible to evaluate the possible solutions of using virtual water to improve the efficiency of water consumption in order to determine the approach of virtual water business to decrease the loss of water resources. The rest of the paper is organized as follows. In the second section, a historical study of past research is presented. In the third section, mathematical modeling and its details are explained. In the fourth section, the results of applying the mathematical model are presented, and finally, in the fifth section, a conclusion is provided along with suggestions for future research.

2. Literature Review

In a 2016 paper, Fracasso et al. investigated the main determinants of the bilateral virtual water (water used in the production of a commodity or service) flows associated with international trade in agricultural goods across the Mediterranean basin. In this research, they considered the bilateral gross flows of virtual water in the area and studied what export-specific and import-specific factors were significantly associated with virtual water flows. They followed a sequential approach. Through a gravity model of trade, they obtain a "refined" version of the variable they aimed to explain, one that is free of the number of flows due to pair-specific factors affecting bilateral trade flows and that fully reflects the impact of country-specific determinants of virtual water trade. A number of country-specific potential explanatory variables, ranging from water endowments to trade barriers, from per capita GDP to irrigation prices, was presented and tested. To identify the variables that help to explain the bilateral flows of virtual water, they adopted a model selection procedure based on model averaging. Their findings confirm one of the main controversial results in the literature: larger water endowments do not necessarily lead to a larger 'export' of virtual water, as one could expect. They also found some evidence that higher water irrigation prices reduce (increase) virtual water 'exports' ('imports'). In 2017, Chen et al. studied China's water footprint in the province and the international transfer of virtual water. The concepts of virtual water and water footprints provide a new approach to alleviate regional shortages of Chinese water resources by the inter-provincial allocation of commercial water resources. In this study, an interregional input-output model was applied to quantitatively estimate the water footprint of each province in China and to quantify the inter-provincial transfer of virtual water. The results indicated that there was considerable diversity in the water footprints of the various provinces. Provinces with larger populations and greater GDP had larger water footprints, and developed regions had higher proportions of external water footprints. From the perspective of final demand, local consumption was the main factor driving the water footprints of these provinces. From the perspective of sectoral structure, the agricultural water footprint had a larger proportion in these provinces. The transfer of virtual water in China did not occur from regions with abundant water resources to those suffering from water shortages, but it generally occurred from west to east, from inland to coastal areas, and from underdeveloped to developed regions. Many water-deficient regions also had large net virtual water exports. Water shortages in China will be alleviated by the enhancement of industrial water-use efficiency in water-deficient regions, the transfer of water-intensive industries to regions with abundant water resources, and the development of tertiary industries with low water consumption. In a 2017 paper, Wang et al. studied agricultural water rights trading and virtual water export in an irrigation district in China and then developed a multi-objective bi-level programming model. The model was applied in Hetao irrigation district by using the enumeration method. The changes of new water use of different users, benefits of irrigation district and water users with different water prices were analyzed and the optimization schemes were selected. Results show that the model through adjusting price variables including both water rights trading price and virtual water compensation price optimizes the allocation of agricultural water quantity saved among different water users, which at the same time makes both the irrigation management administration and water users get more benefit. The optimized scheme can raise the willingness of water saving in irrigation districts, and enhance the competitiveness of agricultural water users against non-agricultural water user. This study provided a new method and scientific basis for the water resource management agency in their policy making. In 2018, Aviso et al. published a paper entitled "A multi-region input-output model for optimizing virtual water trade flows in agricultural crop production". They stated that the onset of climate change is expected to result in variations in weather patterns which can exacerbate water scarcity issues. This can potentially impact the economic productivity of nations as economic activities are highly dependent on water especially for agricultural countries. Environmentally extended input-output models (IOMs) are often used to analyze interactions between economic and ecological systems. However, in this research, a multi-regional input-output model is developed for optimizing virtual water trade between different geographic regions in consideration of local environmental resource constraints, product demands, and economic productivity. In 2018, Quanliang et al. studied the optimal allocation of physical water resources integrated with virtual water trade in water-scarce areas in a case study for Beijing, China. This study provides an innovative application of virtual water trade in the traditional allocation of physical water resources in water-scarce areas. A multi-objective optimization model was optimized to optimize the allocation of physical and virtual water resources to different water users in Beijing, considering the trade-offs between economic benefits and environmental effects of water consumption. In 2018, Chouchane et al. examined virtual water trade patterns in relation to environmental and socioeconomic factors in a case study for Tunisia. This study aimed to analyze the dynamics in virtual water trade of Tunisia in relation to environmental and socio-economic factors such as GDP, irrigated land, precipitation, population, and water scarcity. In 2019, Li et al. studied the efficient-equitable-ecological evaluation of regional water resource coordination considering both visible and virtual water. In this paper, a methodology for a comprehensive evaluation of regional water resource coordination, in which both visible and virtual water were considered in the indicator system was developed. In 2019, SreeVidhya and Elango conducted a study entitled "temporal variation in export and import of virtual water through popular crop and livestock products by India". The objective of this research was to quantify the temporal variation in the virtual water trade in India from the year 2006–2016 through popular food and livestock products. In 2019. Wu et al. conducted an article entitled "global socio-hydrology: an overview of virtual water use by the world economy from source of exploitation to sink of final consumption". This article explored global virtual water use from source of exploitation to sink of final consumption via interregional trades within the world economy as reflected by world input-output database for 2014. An embodiment accounting model was developed, which took full account of virtual water feedbacks related to primary inputs. Global total trade volume of virtual water was estimated to be in magnitude around 30% of the global direct freshwater withdrawal. Moreover, it was revealed that global virtual water transfer in intermediate trade was in magnitude around 1.4 times that in final trade. In 2020, Zhongwen et al. conducted an article entitled "inequality of water allocation and policy response considering virtual water trade: A case study of Lanzhou city, China". They stated that water allocation management that balances the trade-off between economic development and environmental protection. In this study, by introducing a relationship between water and food, they introduced the virtual water trade in the proposed model and case study, and according to the effects of climate changes on seasonal water supply, this study divided the planning of year by season, and finally formulated and applied a bi-objective dynamic model for water allocation in a water-arid area in China. This study aimed to produce an optimal water resource allocation strategy among industrial, domestic, agricultural, and ecological sectors and revealed the effects of variable precipitation on the water allocation strategy. In 2020, Yao et al. published a paper entitled "a novel data-driven analytical framework on hierarchical water allocation integrated with blue and virtual water transfers". This research ensures the optimal allocation of blue and virtual water transfers under different hydrological and economic conditions. A Stackelberg–Nash–Harsanyi equilibrium model was also developed to deal with the hierarchical conflicts between the water affairs bureau and multiple water usage sectors and overcome problems associated with water scarcity and uneven distribution. In 2020, Brindha investigated and studied Virtual water flows, water footprint and water savings from the trade of crop and livestock products of Germany. In this research, comprehensive assessment of the virtual water trade of Germany with the world was performed and the national water footprint through the trade of crop and livestock products from 1991 to 2016 was assessed. Heydari Kushalshah et al. (2023) presented a hybrid planning using mathematical modeling and system dynamics in their study. They used mathematical modeling to determine the key factors for predicting water resources management in Guilan province in order to provide programming for water security. Based on the forecast shown, it was determined that during the next 100 years, the high-precipitation province of Guilan will face a water shortage. Among the domestic studies, we can mention the following studies. For example, Tahamipour and Abedi in 2016 analyzed virtual water trade in the industrial sector of Zanjan province. In this research, they used the information of the census plan from the industrial workshops of 10 workers and more of the Iranian Statistics Center for the year 2010–2011. While categorizing water-requiring industries and the productions of these industries, the amount of water required by them was estimated. The results showed that the highest content of virtual water in Zanjan province belongs to the coking coal production industry and refineries, the paper and paper products manufacturing industry, and the food and beverage industry with averages of 32.70, 26.14, and 11.63 cubic meters per million Rials, respectively. In 2017, Neferzadegan et al. studied the use of interactive interval linear programming for the optimal allocation of water and crop area according to virtual water content and socio-economic factors in a case study in Dorodzan–Karbal plain. The developed model included four goals including socio-economic factors, virtual water content of products, and meeting the water needs of the environment. To solve the model, four scenarios (assumptions) were considered for the cultivation levels. In 2016, Kakhaki et al. analyzed climate change and virtual water management. In this research, they stated that changing the distribution of food trade is important in measuring the impact of climate change. In 2018, Oweisi et al. conducted a study entitled virtual water and ecological footprint of water in Isfahan province's water wheat crop. In this research, they believe that Isfahan province is facing a water crisis considering the recent droughts, climate changes, and growing population, as well as the expansion of industrial and agricultural activities. Therefore, in order to deal with this crisis, it is necessary to consider basic solutions, including the virtual water survey and the water ecological footprint of strategic products in the agricultural sector to manage water resources at risk. The purpose of this study was to investigate the virtual water and the ecological water footprint of the wheat crop in Isfahan province from the crop year of 2016–2017 to 2014–2015. In 2018, Dehghan et al. investigated and evaluated the amount of virtual water and water footprint in the agricultural sector of South Khorasan province. Also, in that research, the results were compared with the amount of virtual water in the water industry sector of the province. In this research, the average virtual water of major agricultural products in South Khorasan province was about 2900 cubic meters for the production of each ton of product, which was estimated to be about 21 cubic meters per ton for the water-consuming industries of the province. In 2019, Abu Torabi et al. estimated the water footprint and virtual water to determine the optimal cropping pattern in a case study for Qaenat and Zirkouh cities. They stated that in order to avoid the negative consequences of the negative water balance in Qaenat and Zirkouh cities, it is necessary to limit the cultivation of crops with high water requirements. In this research, using non-linear multi-objective programming (MOP), an optimal cultivation pattern with the aim of maximizing net profit and minimizing virtual water, green, blue, gray, and white-water footprints of crops in Qayenat and Zirkouh was proposed. In 2019, Baghbanian et al. studied the application of goal programming in determining the optimal pattern of crop cultivation with an emphasis on virtual water in Kurdistan. Therefore, their study was planned and implemented with the aim of economic evaluation of the optimal pattern of crop cultivation in Kurdistan province by its cities with an emphasis on minimum virtual water. In 2019, Hekmatnia et al. determined and evaluated the footprint of green, blue, and gray waters in the international trade of Iran's agricultural products. They stated in this research that to reduce the water crisis, the international trade of agricultural products can play a significant role in the redistribution of water resources because the traded goods contain a large amount of virtual water. In 2019, Koadkhodaei investigated the applications of virtual water in the management of water resources and consumption in Iran. In this paper, the applications of virtual water in the management of water resources and consumption in Iran were compared and evaluated using the TOPSIS method. In 2019, Kolahi et al. conducted a studied entitled "optimization of the cultivation pattern based on the concept of virtual water using linear programming in the Gonabad plain area, Razavi Khorasan province. Accordingly, the purpose of their research was to determine the optimal cultivation pattern based on the concept of virtual water and economic profitability using linear programming in the Gonabad plain. In 2021, Safdari et al. conducted a study entitled "water consumption footprint and virtual water trade of dates in Iran". Therefore, the purpose of this research was to investigate the footprint of water consumption of date cultivation in Iran using three special waters, namely blue water, green water, and gray water. Then, using the concept of virtual water footprint, the water trade footprint was calculated for the date product during 2001–2018. By reviewing the previous background and the research conducted on virtual water allocation, it was observed that the proposed method by providing a mathematical model can be more efficient than other methods. Therefore, according to the examination and review of the theoretical foundations, bi-level mathematical modeling has yet to be performed. Also, this has not been considered in the studied industry and province. Therefore, the present research is carried out with the applied research approach in line with this goal, so as to take a step in meeting the needs of the relevant industry in the desired geographical area in this regard. Hence, in this research, a bi-level mathematical model is designed to allocate virtual water in the food industry of Khuzestan province.

3. Methodology

In terms of thematic scope, this research proposes a bi-level mathematical model of virtual water allocation, determining the exact solution of the mathematical model in GAMS software using the epsilon constraint algorithm. Furthermore, it is solved using NSGA-II and MOPSO meta-heuristic algorithms. In terms of spatial scope, this research extracted the required data from the food industries of Khuzestan province. Thus, the specifications of all food manufacturing companies and factories in this province with types of products and their specifications and addresses are given below. Out of a total of 148 food industry companies, 134 active companies are identified in 16 cities of this province. In terms of time scope, this research collected the required data from the desired sources in the time interval of winter 2019 to spring 2020 (1398 to 1399 in Iranian calendar). Therefore, in this research, a bi-level model based on mathematical programming is used to allocate virtual water in the food industry of Khuzestan province. By introducing the assumptions governing the model, the parameters, variables, objective functions, and constraints of the mathematical model are stated in the following.

Assumptions of the mathematical model

Assumption 1: The budget limit is taken into account.

Assumption 2: Each dam can supply water to several cities.

Assumption 3: Every city can get water from several dams.

Notation
In Table 1, sets, parameters and variables symbol defined.

Table 1. Symbolization

Symbol	Description
Sets	
Symbol	Description
I	Set of dams
J	Set of cities
K	Set of manufacturers (towns or factories)
T	Set of periods
O	Set of sequences of water transfer to producers (towns or factories)
Indices	
Symbol	Description
$i \in I$	Index belonging to the set of dams
$j \in J$	Index belonging to the set of cities
$k \in K$	Index belonging to the set of producers (towns or factories)
$t \in T$	Index belonging to the set of periods
$o \in O$	Index belonging to the set of sequences of water transfer to manufacturers (towns or factories).
Parameters	
Symbol	Description
dk_{kt}	The required amount of gray water in the manufacturing complex
U_j	Total number of manufacturing centers connected to city j
cap_i	Capacity of the i-th dam
b_t	Initial budget
M	A very large number
tdj_{jk}	Time interval between the city and manufacturing complex k
ts_{jk}	Time interval within the manufacturing complex (towns) k located in the j-th city
$td_{kk'}$	Time interval between manufacturing complex k and manufacturing complex k'
cd_{ijt}	Water transfer cost based on the flow rate per unit of distance from the i-th dam to the j-th city
w_{jk}	Time-weighted importance of the k-th manufacturing complex in the j-th city
$Velocity_{ijt}$	Velocity of water from dam i to city j in period t
TE_{ijt}	The amount of time it takes for water to reach city j from dam i $TE_{ijt} = \frac{dis_{ij}}{Velocity_{ijt}}$
$perc_i$	Usable percentage of water capacity of the i-th dam
UTW_k	Upper limit of the time window for the k-th manufacturing complex
LTW_k	Lower limit of the time window for the k-th manufacturing complex
α_{kj}	If the k-th manufacturing complex is in the j-th city, one, otherwise zero
Variables	
Symbol	Description
x_{ijt}	If water is transferred from the i-th dam to the j-th city in period t, one, otherwise zero
z_{jkot}	If the k-th manufacturing complex k belongs to city j in sequence (order of water transfer) o in period t, one, otherwise zero
y_{ijt}:	Amount of virtual water transferred from the i-th dam to the j-th city in period t
ct_{jkt}	The time of completion of water transfer to the k-th manufacturing belonging to the city in period t
TA_{jt}	Maximum time of water reaching from the dam to the j-th city in period t

Objective Functions and Constraints

$$\boldsymbol{min\ z1} = \sum_{i \in I} \sum_{j \in J} \sum_{t \in T} CD_{ijt} . d_{ij} . x_{ijt}$$

$$\boldsymbol{min\ z2} = \sum_{i \in I} \sum_{j \in J} \sum_{t \in T} Ct_{jkt} . w_{jk}$$

$$\sum_{i \in I} y_{ijt} = \sum_{k \in K} Dk_{kt} . \alpha_{kj} \qquad j \in J, t \in T \qquad (1)$$

$$y_{ijt} \le M . x_{ijt} \qquad i \in I, j \in J, t \in T \qquad (2)$$

$$y_{ijt} \ge x_{ijt} \qquad i \in I, j \in J, t \in T \qquad (3)$$

$$\sum_{j \in J} y_{ijt} \le perc_i . cap_i \qquad i \in I, t \in T \qquad (4)$$

$$z_1 \leq b_t \qquad t \in T \qquad (5)$$

$$TA_{jt} \geq TE_{ijt}.x_{ijt} \qquad i \in I, j \in J, t \in T \qquad (6)$$

$$\sum_{o \in O; o \leq U_j} z_{jkot} = \alpha_{kj} \qquad j \in J, t \in T, k \in K \qquad (7)$$

$$\sum_{k \in K} z_{jkot} = 1 \qquad \forall j \in J, o \in O, t \in T; o \leq U_j \qquad (8)$$

$$ct_{jkt} \geq (TA_{jt} + tdj_{jkt} + ts_{jk}) - M.(1 - z_{jkot}) \qquad \forall j \in J, o \in O, t \in T; o = \qquad (9)$$

$$ct_{j'kt} \geq ct_{jkt}(td_{kk't} + tsj_{jk'}) - (1 - z_{jk'ot} + 1 - z_{jkot}).M \qquad \in J, k; k' \in K, o \in O, t \in T \qquad (10)$$

$$\alpha_{kj}.LTW_k \leq ct_{jkt} \leq \alpha_{kj}.UTW_k \qquad j \in J, o \in O, t \in T \qquad (11)$$

The first objective function calculates the cost of sending to cities in terms of flow. The second objective function calculates the time of sending water to each city as a weighted sum. Constraint (1) determines the amount of water transfer to cities. Constraints (2) and (3) determine the variable x_{ijt} based on the positivity of the variabley_{ijt}. Constraint (4) limits the amount of water transfer to cities based on capacity. Constraint (5) guarantees that the cost amount must not exceed the budget amount. Constraint (6) determines the maximum time for virtual water to reach city j from the dams. Constraint (7) specifies the sequence of water delivery of each manufacturing complex in cities. Constraint (8) guarantees that every sequence o in every city must belong to a manufacturing complex. Constraints (9) and (10) calculate the completion time of water transfer to each manufacturing complex. Constraint and (11) limits the time window of water transfer to each manufacturing set.
Problem solving method

In this research, a certain and meta-heuristic solution is used to solve the proposed model.

3.1. Exact solution method: epsilon constraint

One of the exact methods of obtaining optimal Pareto solutions is the use of the epsilon constraint method, which was first presented by Aljadan. The main advantage of this method compared to other multi-objective optimization methods is its use for non-convex solution spaces, because methods such as weighted sum of objectives lose their efficiency in non-convex spaces. The computing time of an algorithm is one of the important features of any algorithm to evaluate it, since one of the fundamental weaknesses of algorithms based on exact search, such as the epsilon method, is the high limitation of their computing time (Khorshidvand et al., 2021). In this method, one of the objectives is always optimized, provided that we define the highest acceptable limit for the other objectives in the majority of the constraints, and for a two-objective problem, we will have the following mathematical expression.

Min f_1 (x) (12)

Subject to f_2 (x)≤ε_1,f_3 (x)≤ε_2,…,f_p (x)≤ε_(p-1),x∈S

By changing the values on the right side of the new constraints for εs, the Pareto edge of the problem will be obtained. One of the main problems of the epsilon constraint method is the high volume of calculations, because for each of the objective functions turned into a constraint (in number of p-1), several different values of the ε_i values must be tried (Abolghasemian et al., 2020). One of the most common approaches to the implementation of the epsilon-constraint method is that first the maximum and half of each objective function are obtained without considering other objective functions in the space,x∈S. Then, using the values obtained from the previous step, the range associated with each of the objective functions is calculated. If we call the maximum and minimum values of the objective functions by f_i^maxandf_i^min, respectively, then the range of each of them is calculated as follows:

〖r_i=f〗_i^max-f_i^min (13) the range r_i is divided into q_i ranges. Then, for ε_i in the following equation, it is possible to obtain different q_i+1 values can be calculated from the following formula.

ε_i^k=f_i^max-r_i/q_i ×k ;k=0,1,…,q (14)

Where k represents the number of the new point related to ε_i. Using the epsilon method, the above multi-objective optimization problem can be converted into $\prod_{i=2}^{p}(q_i+1)$ single-objective optimization problem. Each sub-problem has a solution space S, given that it will be further constrained by the inequalities associated with the objective functions $f_2,...,f_p$. Each sub-problem leads to a candidate solution for the desired multi-objective optimization problem or Pareto optimal front. Sometimes some sub-problems create unjustified space. Finally, after obtaining the optimal Pareto front, the decision maker can choose and use the most appropriate solution.

Meta-heuristic solution method: Non-Dominated Sorting Genetic Algorithm II

Non-dominated sorting genetic algorithm (NSGA-II) is one of the most popular and widely used optimization algorithms in the field of multi-objective optimization. This algorithm was introduced by Deb in 2002. Along with all the functions that NSGA-II has, it can be considered as the model for the formation of many multi-objective optimization algorithms. This algorithm and its unique way of dealing with multi-objective optimization problems have been used many times by different people to create newer multi-objective optimization algorithms. Undoubtedly, this algorithm is one of the most basic members of the evolutionary multi-objective optimization algorithm collection, which can be called the second generation of such methods. In order to implement the NSGA-II algorithm, first, the initial parent population P is created. The population is sorted according to the sorting algorithm and its Pareto front rank is assigned to each individual. Now, the multiple optimization problem is converted into a simple problem of minimization of Pareto front utility function. The selection operators of binary tournament, crossover, and mutation are used to create a population of children Q with the number of N children. From this generation onwards, the way of working will be different due to the application of the process of elitism. In the process of elitism, a mixed population of parents and children is first formed. Then, the mixed population is sorted based on the swarm comparison operator and its N best individuals are considered as the next generation population Pt+1. Then, using N population of Pt+1 and using selection, crossover, and mutation operators, N population of Qt+1 is made. In this algorithm, the diversity of the population in each generation will be guaranteed by applying the swarm comparison operator when selecting the binary tournament, in which there is no need for sharing parameters. Therefore, it will not have the weakness of other methods such as NSGA. Also, the crowding distance is calculated in the space of utility functions, which of course can also be calculated with the space of parameters. Another point is that in making the population of each generation, the selection method of a+b is used instead of (a,b), which will increase the stability of the method and ensure that the good people of the previous generation are not removed in the new generation. Figure 1 illustrates the implementation of the NSGA-II method.

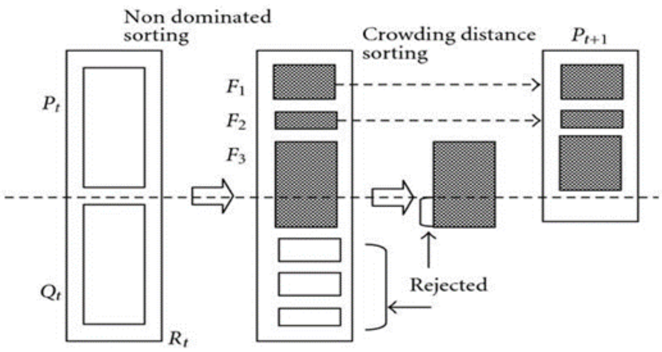

Figure 1. General procedure of implementing the NSGA-II method

Meta-heuristic solution method: particle swarm optimization algorithm

In the particle swarm optimization (PSO) algorithm, each solution is only one particle in the search space and is called a member. All particles have a merit value, which is evaluated by the merit function to be optimized. Moreover, each particle i has a position in the D-dimensional space of the problem in the t-th iteration of the problem, which is represented by a vector in the form of Equation 15.

$$X_i^t=(x_{i1}^t,x_{i2}^t,\dots,x_{iD}^t) \quad (15)$$

Also, this particle has a velocity that is determined by the following vector shown in Equation 16 in the t-th iteration.

$$V_i^t=(v_{i1}^t,v_{i2}^t,\dots,v_{iD}^t) \quad (16)$$

This particle also carries a memory of its previous best position in each iteration, which is represented by the vector P, according to Equation 17.

P_i^t=(p_i1^t,p_i2^t,…,p_iD^t) (17)

In each search iteration, each member is updated considering the two best values. The first one is related to the best solution that the particle has experienced so far (the merit value of the best solution is also stored). This value is called the best P or Pbest. The second best followed by the particle swarm optimization algorithm is the best position ever achieved in the population. This optimal value is general and is called Gbest. When a member considers a part of the population as the topology of its neighbors, the best value is a local best and is called Lbest. After the two best values are found, the position and velocity of each member are updated by Equations (18).

V_i (t+1)=w(v_i)(t)+c_1 r_(1,i) (t)((P_i)(t)-X_i (t))+c_2 r_(2,i) (t)((P_g)(t)-X_i (t)) (18)

x_i (t+1)=X_i (t)+v_i (t+1)

In the above formulas, t represents the iteration number and variables c_1,c_2 are learning factors that control the displacement of a particle in one iteration. r_1,r_2 are two uniform random numbers within the interval [0,1]. w is an algebraic weight that is initialized within the interval [0,1]. A larger algebraic weight facilitates a general exploration and a smaller algebraic weight facilitates a local exploration. In the standard particles swarm optimization algorithm, the population is initialized with random solutions and until the termination condition is reached, the merit of the population is calculated iteratively, the values of Pbest and Gbest, velocity, and position are also updated respectively. Finally, Gbest and its merit value are expressed as output. The termination condition can be reaching the maximum number of generations or reaching a certain value of merit in Gbest. In the following, Figure 2 displays the schematic structure of the position of the particles, respectively.

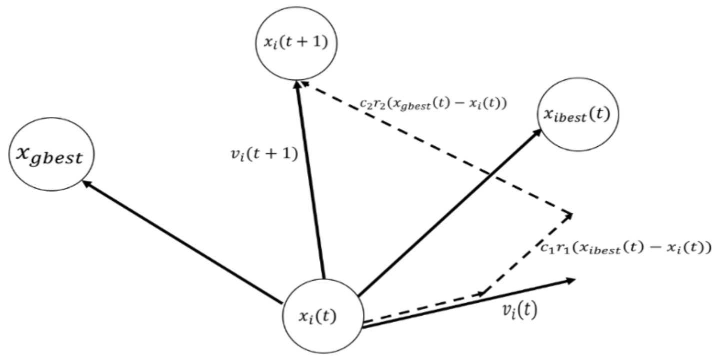

Figure 2. How to update the velocity and position of particles

4. Findings

In order to apply the proposed model in the food industry of Khuzestan province, first, the problems are solved in different dimensions and the resulting results, which include the values of the objective and time functions, are calculated and the effects of increasing the dimensions on these values are compared. Another point is that the sensitivity analysis is carried out on one of the parameters and the effect of increasing or decreasing the usable percentage of the water dam is investigated. First of all, eight problems including small dimensions to real dimensions are introduced as examples. These results are presented in the Tables and Figures below.

Table 2. Parameters determined for the implementation of the mathematical model

Sample No.	Dams	Cities	Manufacturing factories
1	3	4	20
2	4	4	30
3	5	6	40
4	6	8	50
5	7	10	60

Sample No.	Dams	Cities	Manufacturing factories
6	8	12	70
7	9	14	80
8	10	16	92

Table 3. Results of the values of the objective functions and the calculation time based on the examples

Sample No.	Cost	Time	Calculation time
1	1.05E+16	3.27E+06	10
2	1.05E+16	3.39E+06	24
3	1.05E+16	3.57E+06	37
4	1.05E+16	3.74E+06	54
5	1.05E+16	3.84E+06	72
6	1.05E+16	4.01E+06	90
7	1.05E+16	4.17E+06	110
8	1.05E+16	4.35E+06	125

As can be seen in Tables 1 and 2, the values of cost, time, and calculation time changed and increased with the increase in the dimensions of the problem. To make it clearer, the results of the changes are shown in Figures 3 to 5.

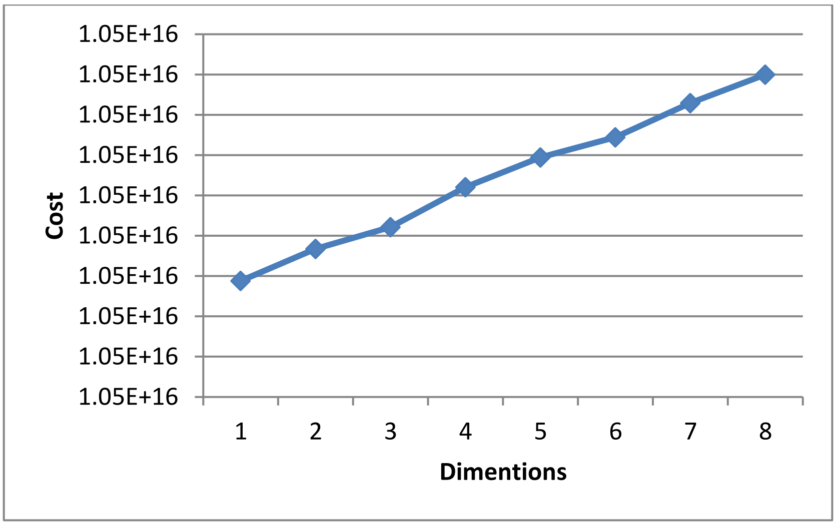

Figure 3. Increase in cost due to increase in dimensions

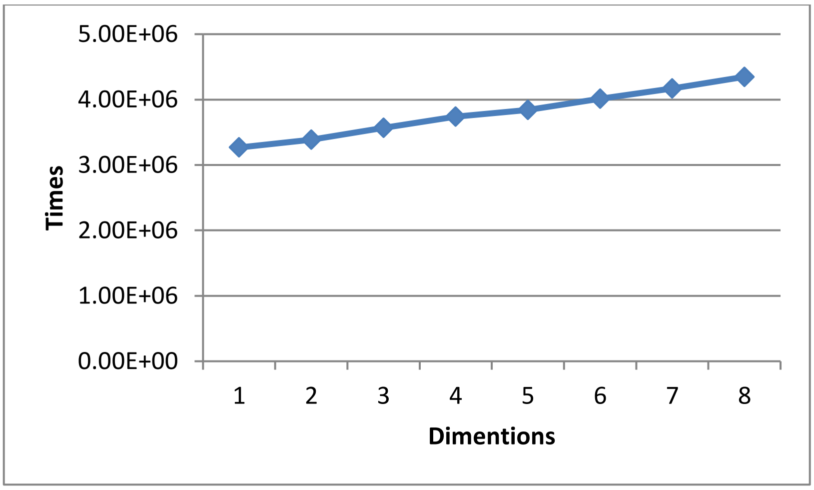

Figure 4. Increase in time due to increase in dimensions

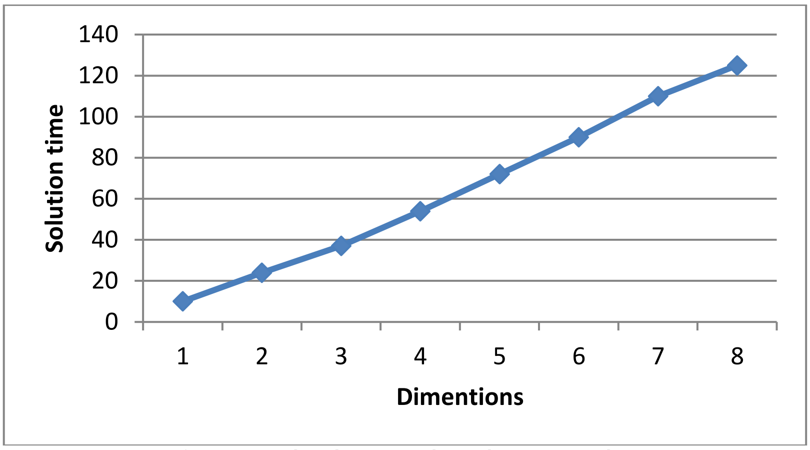

Figure 5. Increase in the solution time due to the increase in dimensions

As it can be seen, the reaction of the cost, time, and calculation time to the increase in dimensions of the problem is positive and upward; therefore, it can be said that the validity of the problem can be confirmed in terms of the increase in dimensions, but another type of validation will be done in the following, which is presented in Table 4 and Figure 6.

Table 4. Change in usable percentage of water dam

Usable percentage of water dam	Dez-Andimeshk dam	Karun-Izeh dam	Jarreh-Ramhormoz dam
70%	198147	19519	25579
75%	214004	21319	27357
80%	230581	23020	29144
85%	241543	24413	31140
90%	259370	25817	32428
95%	277136	27376	33791

In Table 4, it can be seen that the usable percentage of the water dam has changed. Naturally, the increase in the usable percentage of the water dam can affect the capacity of the water dam and thus increase the variable amount of water transfer. In the above table, this action has been taken and at the end, the researcher is looking for the response of the decision variable to the increase in the usable percentage of the water dam. It is assumed that the use capacity is 70% at the beginning and then it increases to 95%. The result is presented in the Figure below.

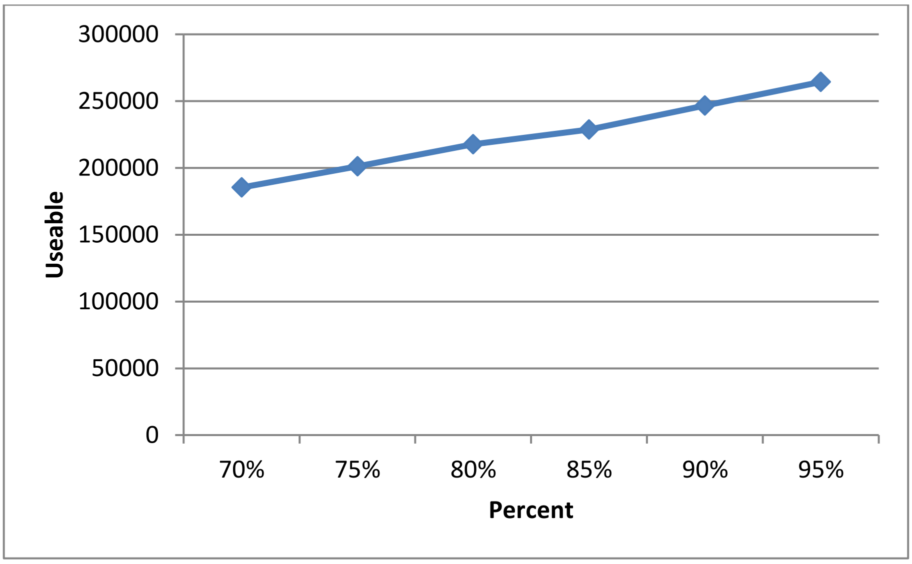

Figure 6. Change in usable percentage of Dez dam

As can be seen in Figure 6, with the increase in the use percentage of the capacity of the Dez dam, the amount of water sent to Andimeshk city, which is considered as a decision variable in the present problem, increases. This is also done for two other water dams that are presented as examples.

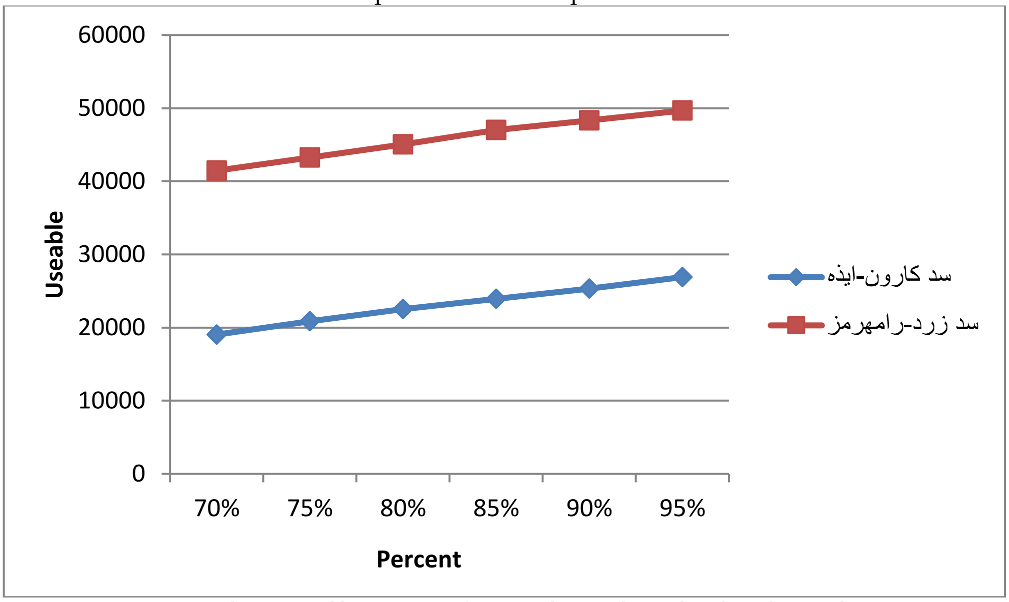

Figure 7. Change in usable percentage of Karun-Izeh water dam and Zard-Ramhormoz dam

In Figure 7, it can be seen that this increase has also taken place in the case of Karun-Izeh and Zard-Ramhormoz dams, as a result, it can be said that the decision variable of the problem, which is the amount of water transfer, has affected the change in the usable percentage of water dams, and from this point of view, it can be said that the problem has the required validity. After confirming the validity of the model, the numerical results obtained from solving the model are presented. These results are presented in the form of two main variables, i.e., the amount of water sent from each dam to each city, as well as the order and sequence of water supply to manufacturing complexes in each city. First, the amount of water supplied by dams to cities is discussed in Table 5.

Table 5. Amount of water supplied by dams to each city

City	Dez	Karkhe	Balaroud	Karoun 3	Ariobarzan	Marun	Jarreh	Gotvand	Masjed Suleiman	Shahid Abbaspour
Andimeshk	628333901.2	1.54E+09	33229268	0	0	0	0	6.99E+08	74602102	78968553
Ahvaz	0	58939096	0	0	0	5.41E+08	59132328	3.82E+08	27484985	0
Izeh	0	0	0	0	0	0	31765120	0	3.77E+08	7.24E+08
Abadan	0	0	0	0	0	0	0	0	0	0
Baghmolk	0	0	0	2.08E+09	7830189	0	44844876	0	1.06E+08	1.38E+08
Bandar-e Emam Khomeyni	0	0	0	0	10962264	28792099	10899796	0	0	0
Behbahan	0	0	0	0	55124528	4.66E+08	16505406	0	0	0
Khorramshahr	0	0	0	0	0	0	0	0	0	0
Dezful	660674616.7	1.45E+09	30886179	0	0	0	0	7.7E+08	1.18E+08	1.58E+08
Ramhormoz	0	0	0	8.87E+08	25683019	1.64E+08	49827639	0	1.14E+08	1.51E+08
Susangerd	0	0	0	0	0	0	1245691	0	6.75E+08	0
Shadgan	0	0	0	0	0	0	0	0	0	0
Shush	503591141.4	1.43E+09	24708943	0	0	0	0	5.76E+08	0	0
Shushtar	406568994.9	7.66E+08	18744715	0	0	0	14325446	9.58E+08	3.65E+08	5.66E+08
Gotvand	401948892.7	7.54E+08	18531707	0	0	0	4359918	1.16E+09	2.36E+08	3.55E+08
Masjed Suleiman	110882453.2	0	4899187	0	0	0	27093779	5.37E+08	5.22E+08	9.67E+08
Total capacity of dam	2712000000	6E+09	1.31E+08	2.97E+09	99600000	1.200.000.000	2.6E+08	5.08E+09	2.62E+09	3.14E+09

As can be seen in Table 5, the amount of water sent from each dam to each city is listed in the above table. According to the distance, this value is determined and the result shows that some dams do not supply water to some cities due to the lack of optimality; therefore, its value has reached zero for each city. On the other hand, the total amount of water supply, for example, from the Dez dam to all cities should not be more than the total capacity of the dam, which is given in the above table. For example, the amount of water supplied by the Dez dam to the city of Masjed Suleiman is 110882453.2, while this dam does not supply water to the cities of Shadgan, Susangard, and Ramhormoz; therefore, its value is equal to zero. In the following, the sequence of water supply to the manufacturing complexes will be discussed, and due to the high volume of manufacturing complexes in each city, only one example, that is, the manufacturing complexes located in Ahvaz city, will be considered. The result is presented in Table 6.

Table 6. Order and sequence of water supply to manufacturing complexes in Ahvaz city along with supply time

Order & Sequence	Manufacturing complex	Supply time
1	Salman Farsi Cultivation and Industry	1471
2	Ard Jonub	1714
3	Bam Laban Tehran	1951
4	Amirkabir Sugarcane Sultivation and Industry	2140
5	Khosh Khorak Hamburger Cooperative No. 262	2332
6	Bahamin Jonub	2601
7	Ahvaz Mahziar Flour	2711
8	Ahvaz Ghonche Flour production	2855
9	Beh Khorak Meat Products	3069
10	Ahvaz Isargaran Cooperative No. 572	3237
11	Khuzestan Canning	3483
12	Dez Macaron	3606
13	Mohanna Noush	3873
14	Paniz-e Jonub	4036
15	Gandomin Jonub Macaroni	4310
16	Persian Daroo	4498
17	Ahvaz Momtazan Meat and Food Products	4636
18	Si Del Food	4845
19	Behshad Khuzestan	5027
20	Ara Protein Jonub	5133
21	Arman Dasht-e Jonub	5278
22	Bahar Farah Noush Company	5575
23	Khuzestan Meat industries	5826
24	Paresh Cultivation and Industry	5990
25	Ferdows Kar Khuzestan	6272
26	Javan Omid Ayande	6458
27	Halvashekari Ofogh	6657
28	Passage Food	6823
29	Zamzam Ahvaz	6939
30	Mehrdad Farzam	7207
31	Toloue Ahvaz	7464
32	Mehrshad Rezin	7637
33	Khorramnush Ahvaz	7866
34	Shadmehr Jonub Company	8087
35	Ahvaz Sugar and Sugar Refinement	8189
36	Asor	8323
37	Jonub Jamus Dairy	8493
38	Hakim Farabi Cultivation and Industry	8606
39	Dabal Khazaei Cultivation and Industry	8903
40	Ahvaz Sekhavat Honey Cooperative	9081
41	Ard Khuzestan	9379
42	Yeast and Alcohol of Sugarcane Development and Ancillary Industries	9491
43	Ard Ahvaz	9614

As can be seen in Table 6, the order and sequence of water supply is presented separately for each manufacturing complex. In fact, the order and sequence of water supply to manufacturing complexes in Ahvaz city according to Table 4 is in an optimal state and based on the time spent, it is better to have the water supply sequence as above.

Meta-heuristic solution of the model

Given the use of two meta-heuristic algorithms NSGA-II and MOPSO in the present problem, the comparison of these two algorithms is discussed in terms of the efficiency of providing solutions. Four criteria are considered for multi-objective problems: number of Pareto points, dispersion criterion, mid index, and solution time in seconds. Regarding the first criterion, that is, the number of Pareto points, the higher the number, the more efficient the algorithm is, and vice versa. But regarding the next three criteria, i.e., dispersion, mid index or the distance to the ideal point, and the calculation time, the lower these values are, the more efficient the algorithm is. Here, the comparison of algorithms is made from the viewpoint of the relevant criteria

Table 7. Comparison of algorithms in terms of efficiency

Example	Results of multi-objective genetic algorithm				Results of multi-objective PSO algorithm			
	Number of Pareto points	Dispersion criterion	MID index	Solution time in seconds	Number of Pareto points	Dispersion criterion	MID index	Solution time in seconds
1	25	32.6	0.86	10	14	33.6	0.87	14
2	23	186	0.85	24	12	201	0.86	30
3	22	77	0.89	37	6	97	0.9	45
4	21	6.65	0.83	54	7	32.65	0.83	60
5	18	115	0.85	72	8	138	0.87	80
6	15	213	0.96	90	8	234	0.96	97

7	14	8.9	0.95	110	7	10.9	0.93	116
8	12	56	0.94	125	7	61	0.92	130

As can be seen in Table 7, the desired indicators for eight problems are presented separately for two algorithms. In fact, the eight mentioned problems are based on real data. In the table above, these eight examples are solved based on real data using two multi-objective genetic algorithms and particle swarm optimization, and the results are compared based on the four criteria of the number of generated Pareto points, the dispersion criterion, the mid index or the distance to the ideal point, and the solution time.
As can be seen in Figure 8, the multi-objective genetic algorithm generates more Pareto points than the particle swarm optimization algorithm and therefore shows a better performance. This is while by increasing the dimensions of the problem, the number of generated optimal points decreases, indicating that as the problem becomes more difficult, achieving the optimal solution becomes more difficult.

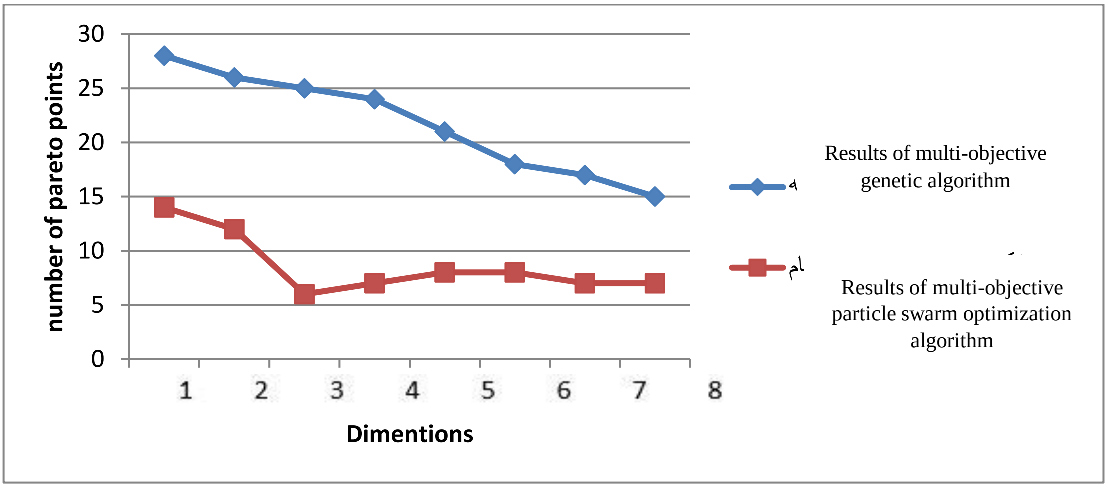

Figure 8. Algorithm comparison in terms of the number of Pareto points

Figure 9 shows that the genetic algorithm created less dispersion than the particle swarm optimization algorithm with a small distance; therefore, in terms of the dispersion, it is in a better situation than the multi-objective particle swarm optimization algorithm.

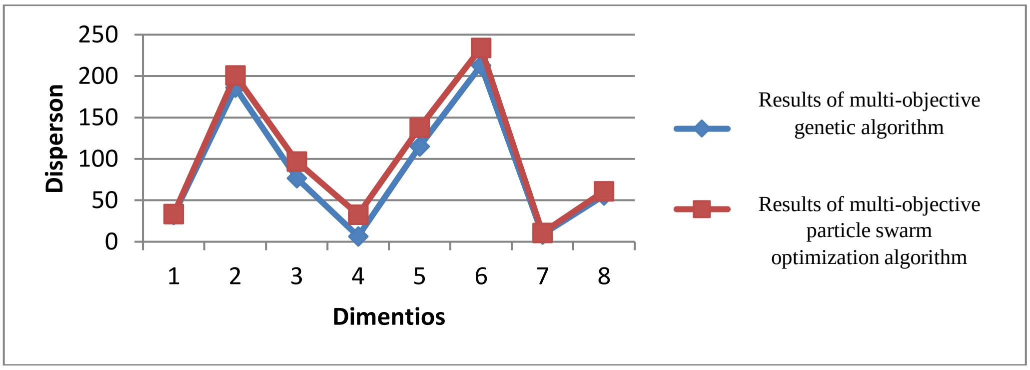

Figure 9. Comparison of algorithms in terms of dispersion

Figure 10 exhibits that the distance to the ideal point increases for both algorithms with the increase in the dimensions of the problem. However, the noteworthy point is that the genetic algorithm performs better than the particle swarm optimization algorithm in most problems in terms of the distance to the ideal point, but in the last two problems which are the most important problems and the last problem which is actually considered the real problem of the present research, the particle swarm optimization algorithm shows better performance. Therefore, regarding the distance to the ideal point, the particle swarm optimization algorithm has a better situation.

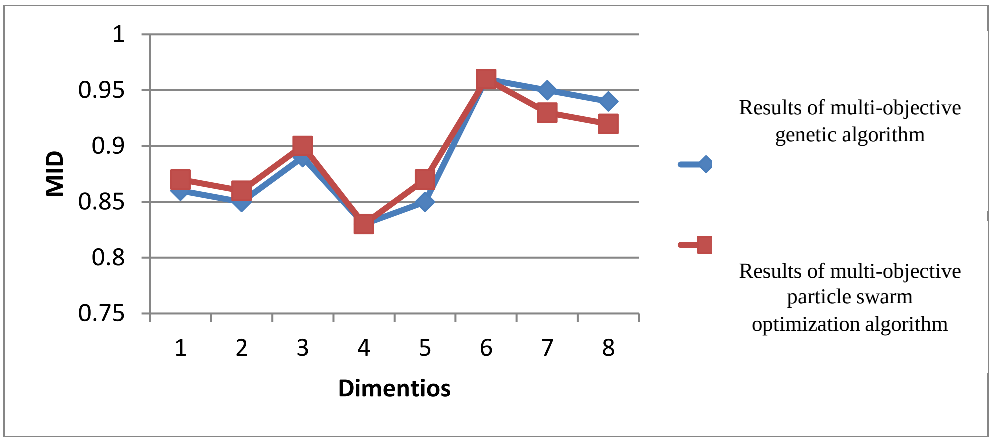

Figure 10. Comparison of algorithms in terms of distance to ideal point

Figure 11 illustrates that there is a small difference between the two algorithms in terms of calculation time, and in general, the genetic algorithm has less calculation time than the particle swarm optimization algorithm. Therefore, in general, it can be said that the multi-objective genetic algorithm has a more acceptable performance than the particle swarm optimization algorithm from the perspective of three criteria, and the particle swarm optimization algorithm has a better situation than the multi-objective genetic algorithm only in terms of the distance to the ideal point. In the following, the results of solving the model and then sensitivity analysis of the problem are discussed.

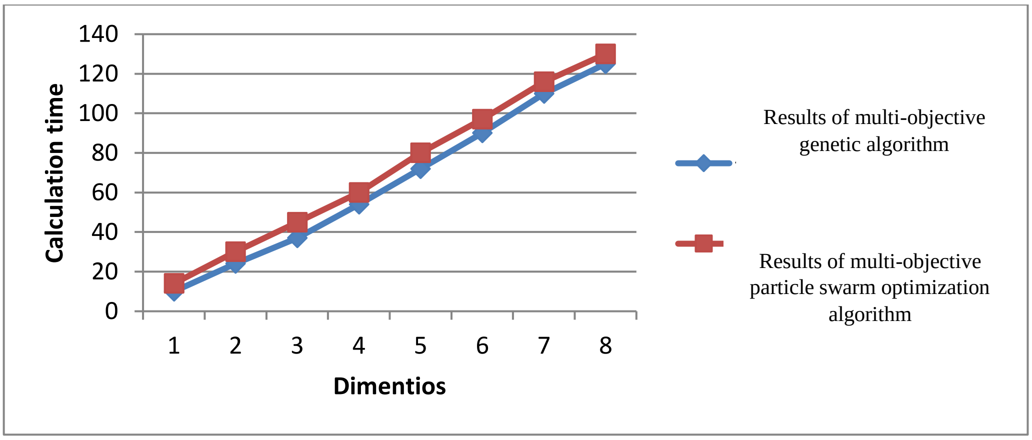

Figure 11. Comparison of algorithms in terms of calculation time

Sensitivity analysis

In this section, the parametric sensitivity analysis of the problem is discussed. Sensitivity analysis is a method to measure the response of the model to changes in parameters and finally find the most effective parameters. In this section, the most important parameters seeming to have the possibility of change are presented and they face an increase within the range of 10 to 50%, and the response to this increase is examined. The results are listed in the form of Tables and Figure below. For this purpose, the effect of different parameters on cost and time is compared and it is determined which parameters have more effect. The results are listed in the Tables and Figure below.

Table 8. Comparison of parameters affecting the cost

Time	Demand	Budget	Time distance between city and manufacturing complex	Time distance within manufacturing complex	Time distance between manufacturing complexes	Water transfer cost	Water supply time
10%	0.000957	0.001668	0.001481	0.000964	0.001032	0.018192	0.001415
20%	0.002331	0.003232	0.002821	0.002716	0.002653	0.03527	0.003236
30%	0.003277	0.005069	0.003807	0.004393	0.004085	0.048147	0.00422
40%	0.004883	0.006246	0.005407	0.005613	0.005893	0.061302	0.005798
50%	0.006708	0.007751	0.006756	0.006802	0.007208	0.069878	0.007352

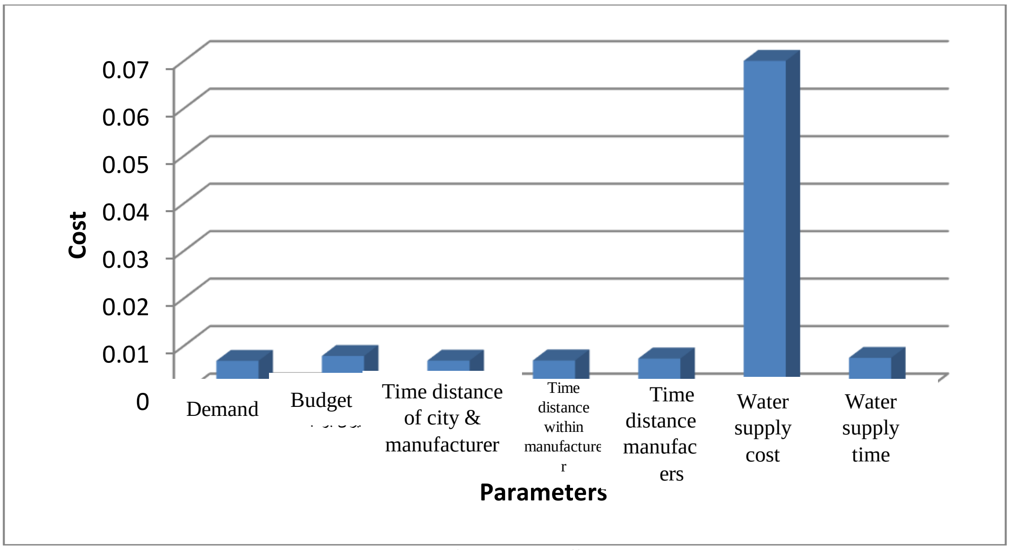

Figure 12. Comparison of parameters affecting cost

As can be seen in Figure 12, the most effective parameter on cost the increase level of 50% is the cost of water transfer which can increase cost by 7%, while the effectiveness of other parameters is just about 0.5% and barely reaches 1%. In fact, the other parameters are almost the same in terms of effectiveness and there is no difference between them; however, the parameter of water transfer cost is the only parameter with a significant effect.

Table 9. Comparison of parameters affecting time

Time	Demand	Budget	Time distance between city and manufacturing complex	Time distance within manufacturing complex	Time distance between manufacturing complexes	Water transfer cost	Water supply time
10%	0.004588	0.003135	0.028758	0.024827	0.03554	0.004038	0.0237
20%	0.007138	0.006735	0.06766	0.047373	0.065165	0.008325	0.058386
30%	0.011622	0.010334	0.102476	0.087981	0.095422	0.012431	0.091643
40%	0.015919	0.012834	0.118233	0.107313	0.113714	0.015628	0.121867
50%	0.018921	0.01663	0.132082	0.132367	0.129649	0.018575	0.131448

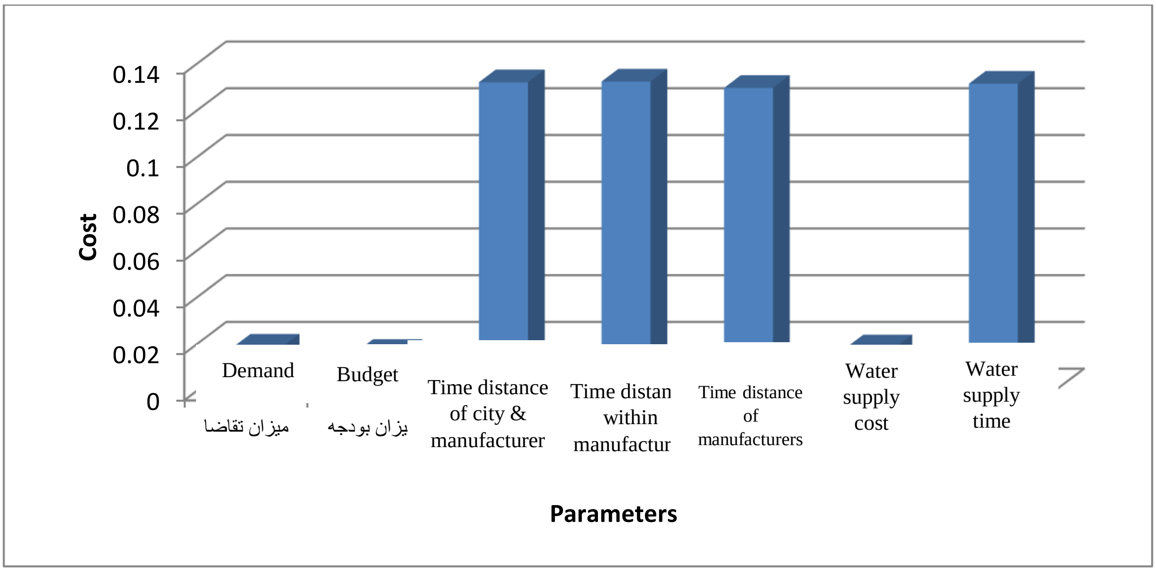

Figure 13. Comparison of parameters affecting cost\

The parameters affecting time are compared in Figure 13. As can be seen, the time distance between the city and the manufacturing complex, the time distance within the manufacturing complex, water supply time, and the time distance between the manufacturing complexes have the highest effect with a value of around 13%. In fact, the effectiveness of the above parameters on the water transfer time is generally almost the same and has a considerable distance with parameters of demand, budget, and water transfer cost. According to the results obtained, it can be said that the parameters of demand, budget, and water transfer cost have little effect on water transfer time with a value less than 2%, while the parameters of time distance and water supply time, considering the nature of time that they have, have the highest effect with a value of approximately 13%.

5. Conclusions

This research aims to optimize the use of water resources of dams in Khuzestan province. For this purpose, library studies were first conducted and the research gap in the studied area was discovered. Then, research objectives and assumptions were determined based on the innovation, and then a multi-objective mathematical programming model was designed based on the assumptions. The cost and time of sending water to each city from all dams in Khuzestan province were optimized. The model was optimized using the epsilon constraint method. One of the issues identified in the present research is determining the optimal water supply to cities from dams. Based on this variable, there were cities that are not supplied with water from some dams, indicating the lack of optimal water supply. For example, in the optimal state, it is better not to supply water to the cities of Shadgan, Susangerd, and Ramhormoz. Because supplying water to these cities from Dez dam is not economical in terms of time and cost. While the Dez dam can supply water to the city of Masjed Suleiman up to an acceptable volume. This can be seen in other dams as well. For example, according to the results presented in the presented research, water supply from Balaroud dam to the cities of Ahvaz, Izeh, Abadan, Baghmolk, and Bandar-e Emam Khomeyni are identified as optimal. While the same dam supplies a certain amount of water to the cities of Andimshek, Dezful, Shush, Shushtar, and Gotvand. It is of great importance to determine which dams are optimal and which dams are not optimal for water supply, because this can be effective on the policy of sending water from dams and providing better planning in order to prevent water waste. In order to solve it in real and large dimensions, meta-heuristic algorithms NSGA-II and MOPSO were used. In the epsilon constraint method, a small number of dams and cities was considered, but in the meta-heuristic method, the total number of dams and cities was considered. The results showed that the multi-objective genetic algorithm has a more acceptable performance than the particle swarm optimization algorithm from the perspective of three criteria, and that the particle swarm optimization algorithm is better than the multi-objective genetic algorithm only in terms of the distance to the ideal point. Finally, the results of the sensitivity analysis indicated that the increase in water demand can increase the supply time by 1.9% and the supply cost by 60%. Therefore, the effect of water demand is more on time and not on cost. Increasing the budget can have an effect on cost and time, which of course has more effect on time than cost. The next parameter is the time distance between the cities and the manufacturing complex, which is expected to increase the water supply time by 13%, suggesting a relatively significant effect, while this effect is less on the cost of time. Using other meta-heuristic algorithms and comparing them with each other in terms of efficiency and considering other objectives such as risk and reliability of water supply are introduced as suggestions for future research to other researchers.

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