OPTIMIZATION OF VIRTUAL WATER USAGE TOWARDS FOOD SECURITY USING CLASSIC AND MODERN OPTIMIZATION METHODS

OPTIMISATION DE LA CONSOMMATION D'EAU VIRTUELLE VERS LA SECURITE ALIMENTAIRE EN UTILISANT LES METHODES D'OPTIMISATION CLASSIQUE ET MODERNES

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ABSTRACT

The water that would be needed if a certain commodity were to be produced is called the "virtual water". If one country exports a water-intensive product to another country, it exports water in virtual form. For water-scarce countries it could therefore be attractive to achieve water security by importing water-intensive products instead of producing them domestically. In IRAN with low average annual precipitation and lack of other sources of water, the concept of virtual water and its trade is used as a strategy for optimal operation of water resources in many fields. Recently, in IRAN, net virtual water import reached to (15-20)10^9 m^3 per year and is one of the top ten virtual water importing countries. In this paper, the virtual water content in some of the agricultural products in the world have been compared with products in IRAN.*

*Additionally, we selected some strategic agricultural products, which are both exported and imported and used two methods to optimize virtual water usage and trade according to demands, agriculture situation, production cost and environmental condition. In order to optimize the virtual water exchange, we calculated two new parameters by dividing (Consumed water / Yield) with (m^3/Kg) dimension and (Value / Amount) with ($/Kg) dimension, which were used as cost and benefit, respectively. After that, we made objective function to be optimized based on the indicated cost and benefit indexes. The objective functions were: Maximize benefit ((Benefit Index: β) * Production Amount) and Minimize virtual water usage ((cost Index: α)*Production Amount).*

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Optimization was done using two methods: 1- Linear Programming (LP) and 2- Genetic Algorithm (G.A) which is a non-linear method to optimization using evolution rules to complete the process. The method of "G.A." is more flexible and versatile and has been used in different fields of engineering sciences.

Results, show optimum possible cultivation pattern for exported product that minimizes the exported virtual water and maximizes the benefit. Optimization methods also gave another pattern for importing products which causes reduced cost by reducing virtual water import. So, by this pattern, we have 165 million dollars per year increase in benefits and economize 4150 million cu m in virtual water usage for exported products. For imported product, pattern results 2140 million dollars of expenditure per year even though the amount of imported virtual water reduced. Optimization also had resulted in higher revenues and lower cost of exported products. According to optimum fitted pattern, import of "Soya" in importing product category should be increased 29 % and "Pistachio" production for export recommended to increase as 11 %. Recommended pattern for export results about 4015 million cubic meter water saving each year.

Key words: *Virtual water, soya, pistachio, water scarcity, food import-export*

RESUME

L'eau qui sera nécessaire si une certaine marchandise doit être produite est appelée «l'eau virtuelle». Quand un pays exporte un produit dont la production utilise l'eau à un autre pays, il exporte l'eau sous forme virtuelle. Pour les pays des ressources en eau limitée, pour avoir la sécurité de l'eau, il pourrait donc être intéressant d'importer des produits dont la fabrication exige beaucoup d'eau au lieu de les produire localement. En Iran avec des faibles précipitations annuelles moyennes et l'absence d'autres sources d'eau, le concept d'eau virtuelle et son commerce sont utilisés comme une stratégie pour un fonctionnement optimal des ressources en eau dans de nombreux domaines. Récemment, en Iran, l'importation d'eau virtuelle nette a atteint à (15-20)10^9 m^3 par an et est l'un des dix premiers pays importateurs d'eau virtuelle. Dans cette étude, la teneur en eau virtuelle dans quelques uns des produits agricoles dans le monde a été comparée avec les produits en Iran.*

*De plus, nous avons sélectionné quelques produits agricoles stratégiques, qui sont à la fois exportés et importés. Nous avons utilisé deux méthodes pour optimiser l'utilisation et le commerce de l'eau virtuelle en fonction des demandes, de l'état de l'agriculture, des coûts de production et de l'état de l'environnement. Afin d'optimiser l'échange d'eau virtuelle, nous avons calculé deux nouveaux paramètres en divisant (eau consommée / rendement) ayant des dimensions (m^3 / kg) et (valeur / montant) ayant la dimension ($ / kg) où ces deux ont été utilisés comme le coût et le profit, respectivement. Après cela, nous avons fait de sorte que la fonction objective soit optimisée en fonction du coût indiqué et les indices de profit. Les fonctions objectifs sont les suivants: maximiser les avantages = ((Indice de prestation: β) * Volume de production) et minimiser l'utilisation de l'eau virtuelle = ((Indice du coût: α) * Volume de production).*

L'optimisation a été faite en utilisant deux méthodes: 1) – La Programmation Linéaire (PL) et 2) – L'algorithme génétique (GA). Ce dernier est une méthode non-linéaire d'optimisation à *l'aide règles d'évolution pour compléter le processus. La méthode «GA» est plus flexible et polyvalente, qui a été utilisée dans différents domaines des sciences de l'ingénierie.*

Les résultats, montrent le modèle optimal possible pour la culture des produits exportés qui minimise l'eau virtuelle exportée et qui maximise le profit. Les méthodes d'optimisation ont également montré un autre modèle pour l'importation de produits qui coutent moins chers une fois que l'importation de l'eau virtuelle est réduite. Ainsi, par ce modèle, nous avons 165 millions de dollars d'augmentation annuelle des prestations et nous avons pu économiser 4,15 milliards de m^3 dans l'utilisation de l'eau virtuelle pour les produits exportés. Pour des produits importés, ce modèle montre les dépenses annuelles de 2140 millions de dollars, même si la quantité d'eau virtuelle importée a diminué. L'optimisation a également entraîné une hausse des revenus et une baisse du coût des produits exportés. Selon le modèle optimale équipé, l'importation du « soja » dans la catégorie des produits importés doit augmenter de 29% et celle de la « pistache » pour l'exportation doit augmenter de 11%. Le modèle recommandé pour l'exportation montre qu'environ 4,015 milliards m^3 d'eau peuvent être économisés chaque année.

Mots clés : *Eau virtuelle, soja, pistache, rareté de l'eau, importation et exportation de la nourriture.*

1. INTRODUCTION

Iran experiences arid and semi arid climate with 250 mm mean precipitation. About 94 percent of fresh water available in the country is used in agriculture; 5 percent in health and urban usage and 1 percent by the industry. Countries with crucial water conditions introduce a new concept as "virtual water" to their strategic agricultural and industrial productions.

Producing goods and services generally requires water. The water that will be required if a certain agricultural or industrial good were to be produced is called the "virtual water" contained in the product. The concept of 'virtual water' has been introduced by Tony Allan in the early nineties (Allan, 1993; 1994).

For producing 1 kg of grain we need for instance 1000-2000 kg (1 – 2 m^3) of water. Producing livestock products generally requires even more water per kilogram of product. For producing 1 kg of cheese we need for instance 5000- 5500 kg of water and for 1 kg of beef we need in average 16000 kg of water (Chapagain and Hoekstra, 2003). According to a recent study by Williams et al. (2002), the production of a 32-megabyte computer chip of 2 grams requires 32 kg of water.

If one country exports a water-intensive product to another country, it exports water in virtual form. In this way some countries support other countries in their water needs. Trade of real water between water-rich and water poor regions is generally impossible due to the large distances and associated costs, but trade in water-intensive products (virtual water trade) is realistic. For water-scarce countries it could therefore be attractive to achieve water security by importing water-intensive products instead of producing all water-demanding products domestically. Reversibly, water-rich countries could profit from their abundance of water resources by producing water-intensive products for export.

2. VIRTUAL WATER CONCEPTS

There are some important and main introductions and equations which are clues in virtual water concept. Some of the most important of them are as follows:

Virtual Water Conceptual Parameters

Water in the hydrology cycle is divided into two categories: “blue” and “green” water. “Blue water” is the component of the rainfall that moves as surface and subsurface flow ending up in rivers, lakes and groundwater. This is the water that we primarily manage and use. “Green” water in the hydrological cycle, is the rainfall that is intercepted by vegetation and by the soil, and is taken up by plants to create biomass and then evapotranspired back into the atmosphere. This part of the hydrological cycle has not been given much attention and is poorly managed. The blue virtual water content (BVW) was calculated as follows:

$$BVW = \frac{10 \times CIR \times CA_{irr}}{CP_{total}} \qquad (1)$$

where CIR is the crop irrigation requirement (mm), CA_{irr} is the area (ha) of crop under irrigation and CP_{total} is the total amount of maize (tonnes) produced. Estimates of the area of maize under irrigation for each SADC country were obtained from the FAO Aquastat survey (FAO, 2005). Green virtual water content (GVW) was calculated as follows:

$$GVW = \frac{10 \times (CWR - CIR) \times CA_{total}}{CP_{total}} \qquad (2)$$

where CWR is the crop water requirement (mm) and CA_{total} is the total area under maize (ha). So, the total virtual water content is equal to the sum of the green and blue virtual water content for maize in the country.

Specific Water Demand

The Virtual Water Content [VWC] of a crop c in a country (m^3/ton) is calculated as the ratio of total water used for the production [CWU] to the total volume of production by that country (Chapagain and Hoekstra, 2004).

$$SWD_c = \frac{CWR_c}{CY_c} \qquad (3)$$

Where, CWR is the crop water requirement measured at field level (m^3/ha), and Y_c the total volume of crop c produced per hectare in the country (ton/ha).

Crop water requirement is defined as the total water needed for evapotranspiration from planting to harvest for a given crop in a specific region, when adequate soil water is maintained by rainfall and/or irrigation so that it does not limit plant growth and crop yield. Under standard conditions when a crop grows without any shortage of water, the crop evapotranspiration is equal to the CWR of a crop (Allen et al, 1998). The crop water requirement is calculated by accumulation of data on daily crop evapotranspiration ETc (mm/day) over the complete growing period as following:

$$CWR_c = 10 \times \sum_{d=1}^{lp} ET_{c,d} \tag{4}$$

Where the factor 10 is meant to convert mm into m^3/ha and where the summation is done over the period from day 1 to the final day at the end of the growing period (lp stands for length of growing period in days). The crop evapotranspiration per day follows from multiplying the reference crop evapotranspiration ET$_0$ with the crop coefficient Kc as following:

$$ET_c = K_c \times ET_o \tag{5}$$

The reference crop evapotranspiration ET$_0$ is defined as the rate of evapotranspiration from a hypothetical reference crop with an assumed crop eight of 12 cm, a fixed crop surface resistance of 70 sec/m and an albedo of 0.23.

Calculation of Virtual Water Trade Flows and National Virtual Water Trade Balance

Virtual water trade flows between nations have been calculated by multiplying international crop trade lows by their associated virtual water content. The latter depends on the specific water demand of the crop in the exporting country where the crop is produced. Virtual water trade is thus calculated as:

$$VWT_{(ne,ni,c,t)} = CT_{(ne,ni,c,t)} \times SWD_{(ne,c)} \tag{6}$$

in which VWT denotes the virtual water trade (m^3/yr) from exporting country n_e to importing country n_i in year t, as a result of trade in crop c. CT represents the crop trade (ton/yr) from exporting country n_e to importing country n_i in year t for crop c.

The gross virtual water import (GVWI) to a country n_i is the sum of all imports:

$$GVWI_t = \sum_{ni,c} VWT_{(ni,c,t)} \tag{7}$$

The gross virtual water export (GVWE) from a country n_e is the sum of all exports:

$$GVWE_t = \sum_{ne,c} VWT_{(ne,c,t)} \tag{8}$$

The net virtual water import of a country is equal to the gross virtual water import minus the gross virtual water export. The virtual water trade balance of country x for year t, can thus be written as:

$$NVWI_t = GVWI_t - GVWE_t \tag{9}$$

Where NVWI stands for the net virtual water import (m^3/yr) to the country. Net virtual water import to a country has either a positive or a negative sign.The latter indicates that there is net virtual water export from the country.

The Water Footprint of a Country

The total water use within a country itself is not the right measure of a nation's actual appropriation of the global water resources. In the case of net import of virtual water into a country, this virtual water volume should be added to the total domestic water use in order to get a picture of a nation's real call on the global water resources. Similarly, in the case of net export of virtual water from a country, this virtual water volume should be subtracted from the volume of domestic water use. The sum of domestic water use and net virtual water import can be seen as a kind of 'water footprint' of a country, on the analogy of the 'ecological footprint' of a nation. In simplified terms, the latter refers to the amount of land needed for the production of the goods and services consumed by the inhabitants of a country. The 'water footprint' of a country (expressed as a volume of water per year) is defined as:

$$\text{Water Footprint} = \text{WU} + \text{NVWI} \tag{10}$$

In which WU denotes the total domestic water use (m^3/yr) and NVWI the net virtual water import of a country (m^3/yr). As noted earlier, the latter can have a negative sign as well.

National Water Scarcity, Water Dependency and Water Self-Sufficiency

As an index of national "water scarcity" we use the ratio of total water use to water availability:

$$WS = \frac{WU}{WA} \times 100 \tag{11}$$

In this equation, WS denotes national water scarcity (%), WU the total water use in the country (m^3/yr) and WA the national water availability (m^3/yr). Defined in this way, water scarcity will generally range between zero and hundred per cent, but can in exceptional cases (e.g. groundwater mining) be above hundred per cent.

The "water dependency", WD of a nation is in this paper calculated as the ratio of the net virtual water import into a country to the total national water appropriation:

$$WD = \begin{cases} \dfrac{NVWI}{WU + NVWI} \times 100 & if \quad NVWI \geq 0 \\ \\ 0 & if \quad NVWI \prec 0 \end{cases} \tag{12}$$

The value of the water dependency index, by definition, varies between zero and 100 per cent. A value of zero means that gross virtual water import and export are in balance or that there is net virtual water export.

As the counterpart of the water dependency index, the "water self-sufficiency" index is defined as follows:

$$WSS = 1 - WD \tag{13}$$

The level of water self-sufficiency (WSS) denotes the national capability of supplying the water needed for the production of the domestic demand for goods and services. Self-sufficiency is hundred per cent if all the water needed is available and indeed taken from within the own territory. Water self-sufficiently approaches zero if a country heavily relies on virtual water imports.

Global Virtual Water Calculating Process

With reference to the contexts, the commonly adopted process of calculating virtual water is as given in Fig. 1.

Global Virtual Water Trading

In this section, we investigate virtual water trading and subsequent benefits to Iran comparied with some other countries. Virtual water calculating and trading identities in these countries are shown in Table 1.

In this paper, we select two kinds of agricultural products in Iran. First, 16 agricultural products studied which allocate $33.8*10^9$ cubic meter of water export. On the other hand, virtual water importance for 9 studied agricultural products is $46.1*10^9$ cubic meter. Utilized amount of virtual water in mean per tone is 2869.6 cubic meter for exports and 3893 cubic meter for imports. Imported and exported total virtual water by selected products and its values are shown in Tables 2 and 3 respectively.

According to NVWI index (table 1), indicates that Iran is one of the biggest user of imported virtual water.

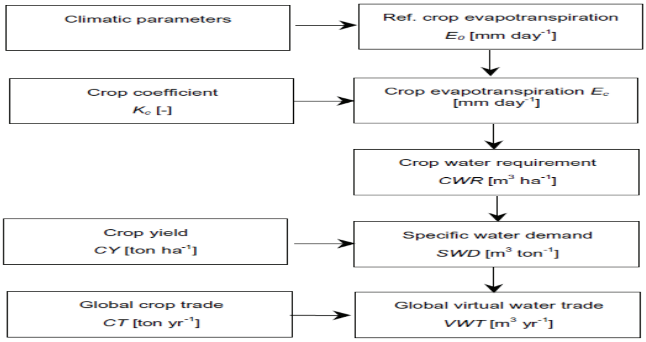

Fig. 1. Calculating Process of Virtual Water

Table 1. Vitual Water Calculating Index

Country	Water Availability	GVWE	GVWI	NVWI	Water Footprint	WS (%)	WSS (%)	WD (%)
Iran	117500	803.4	6623.1	5819.7	1457	72.9	93.6	6.4
Australia	343000	30130.3	1011	-29119.3	1085	8	100	0
Germany	171000	9671.3	13589.1	13589.1	742	27.7	77.7	22.3
Japan	547000	188.4	59443.6	59443.6	1196	16.8	60.7	39.3
Brazil	6950000	32161.8	23161.6	-9000.2	225	0.7	100	0
Cameron	268000	187.9	175.3	-12.6	33	0.2	100	0

3. VIRTUAL WATER EXCHANGE, TRADE AND OPTIMIZATION IN IRAN

According to Table 2 and Table 3, in order to optimize of virtual water exchange, we calculated two parameters by dividing (Consumed water / Yield) with (m^3/Kg) dimension and (Value / Amount) with ($/Kg) dimension which used as cost and benefit. After that, we made object function to optimization by “Genetic Algorithm” based on mentioned cost and benefit indexes.

Table 2. Exported Total Virtual Water, Amount and Value By Selected Products (1996-2004), Iran

Product	Amount (Ton)	Value (1000 $)	Virtual Water Volume (m^3)	Consumed Water (m^3/ha)	Yield (kg/ha)
Grape	4452290	549390	2174514799	8000	4091
Nut	19610	21200	115352941	850	5000
Pistachio	1100790	3757700	20408621090	431.5	8000
Onion	658970	57230	434922685	21212	14000
Tea	90130	61140	179707055	1630	3250
Date	991600	305790	1967460317	6300	12500
Cucumber	69060	17800	7847727	22000	25000
Apple	1590020	273630	636008000	13000	5200
Potato	612550	74140	320731180	25000	13090
Garlic	30070	4730	14729881	14290	7000
Walnut	25350	35260	131688311	1155	6000
Tomato	1851550	260550	608366428	35000	11500
Beans	5390	1120	2964500	10000	5500
Citrus	36440	6060	31617058	170000	14750
Sum	11782850	5520500	33812343300	-	-

Table 3. Imported Total Virtual Water, Amount and Value By selected Products (1996-2004), Iran

Product	Amount (Ton)	Value (1000 $)	Virtual Water Volume (m^3)	Consumed Water (m^3/ha)	Yield (kg/ha)
Sunflower	3934100	1075550	59382641610	530	8000
Peanut	77830	27710	133752296	3375	5800
Rice	10699380	2556230	61139314290	3500	20000
Barely	5245260	783370	9618310000	3000	5500
Tea	112440	310750	224190184	1630	3250
Sorghum	13986640	215420	21221108970	7250	11000
Soya	36906730	5516570	246044866700	1500	10000
Sugar	7669600	1947241	18782693880	4900	12000
Wheat	38135230	5325450	43855514500	5000	5750
Banana	1689470	721240	1013682000	25000	15000
Sum	118520500	20400361	461414074300	-	-

4. OPTIMIZATION

Objective function determined as:

Maximize benefit ((Benefit Index: β) * Production Amount) and Minimise virtual water usage ((cost Index: α)*Production Amount).

Objective function was first optimized by LP model using LINGO software. LP model gives a good examination for the first step of optimization using dual price and reduced cost indexes. Then the non-linear Genetic Algorithm "G.A." was used. Ability of "G.A." in finding global optimization by acceptable iteration makes it an elite method between other algorithms. Specified characteristics of "G.A." change it to a flexible method to use in different fields of engineering sciences.

The "G.A." was run with 1000 initial population and 0.001 accuracy. In 100 iterations, evolution parameters were 0.03 for mutation coefficient and crossover coefficient equal to 0.8.

Results show optimum possible cultivation pattern for exported product. With this pattern, we can minimize exported virtual water content and maximize benefit. On the other hand, "G.A." gives another pattern for importing products that reduce the cost despite a reduction in virtual water import. So, by this pattern, we have 165 million dollars per year increase in benefits and economize 4150 million cubic meter in virtual water usage for exported products. For imported product, pattern results 2140 million dollars providence per year for imported products even though amount of imported virtual water reduced. Optimum patterns for importing and exporting products based on "G.A" results are shown in Fig. 2 and Fig. 3, respectively.

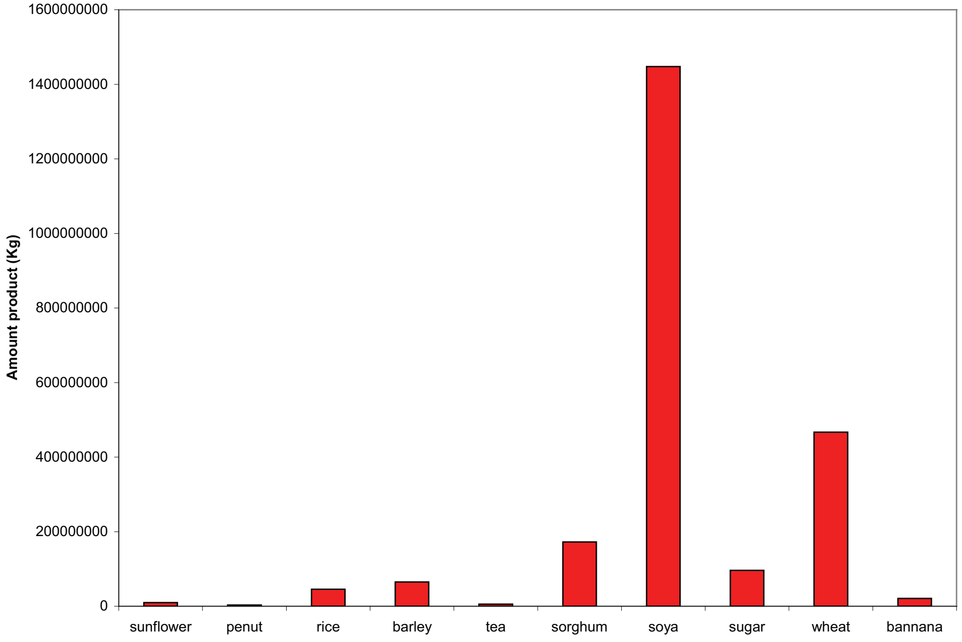

Fig. 2. Optimum pattern for importing aggricultural products

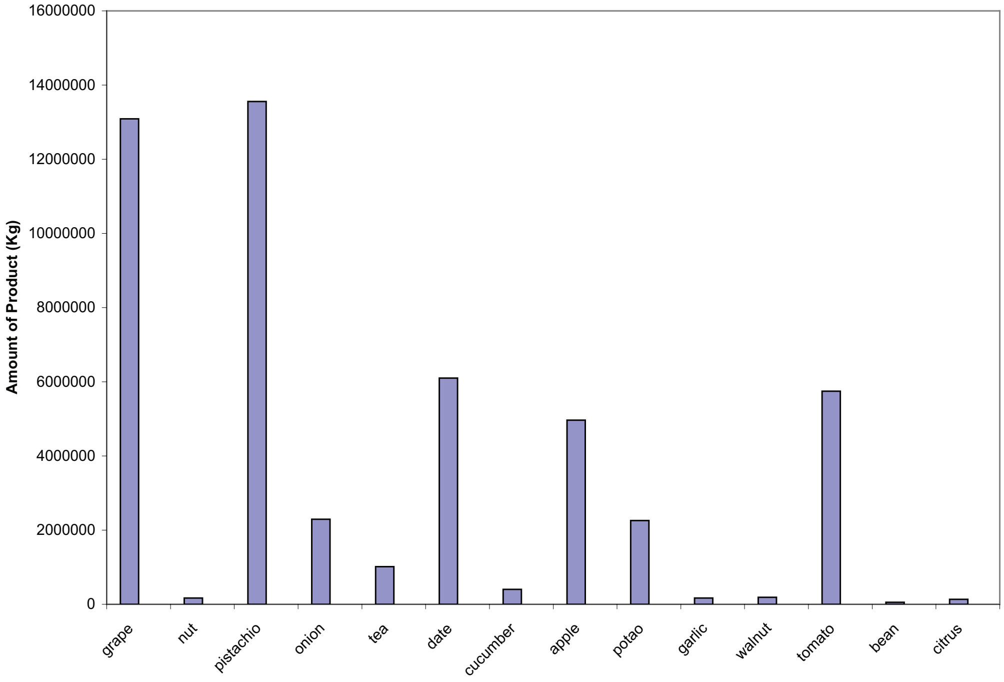

Fig. 3. Optimum pattern for exported agricultural products

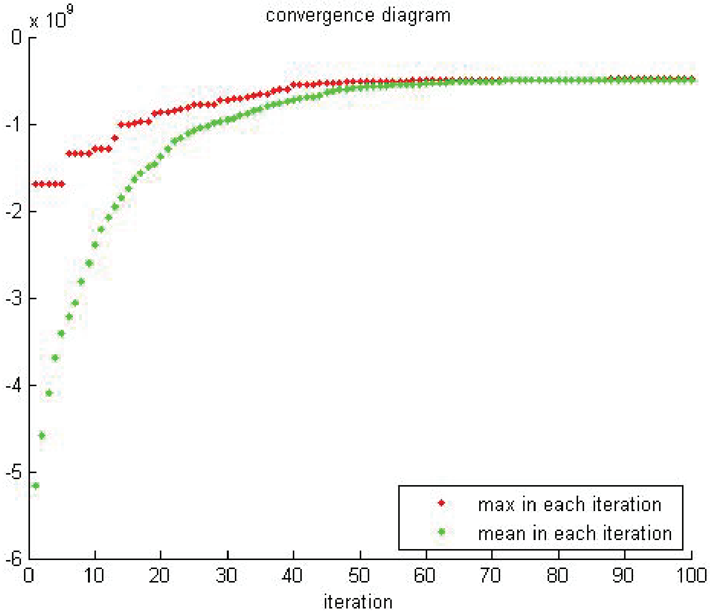

Fig. 4. Convergence Diagram of "G.A" results after 100 iterations

In Fig. 4, convergence trend of programe is seen after 100 iteration and the convergence starts after approximately 70 iterations.

5. CONCLUSIONS

It can be said that the virtual water concept could be a useful and important factor for water scarcity countries or countries with arid or semi arid climates. Additionally, its role in agriculture product trading and national economy exchange rate is considerable.

In this paper, some selected strategic agriculture products and their statistics was studied in Iran. Virtual water parameters were calculated and considered. Object function to optimization mentioned was a combination of cost and benefits functions. Optimization was done by using the LP and the non-linear Genetic Algorithm (G.A.) models. The Results, show optimum possible cultivation pattern for exported product. With this pattern, we can minimize exported virtual water content and maximize obtain benefit. On the other hand, optimization methods give another pattern for importing products which causes reducing in cost despite by reducing virtual water import. So, by this pattern, we have 165 million dollars per year increasing in benefits and economize 4150 million cubic meters in virtual water usage for exported products. For imported product, pattern results 2140 million dollars providence per year for imported products even though amount of imported virtual water reduced. Optimization also had economical results by increasing revenues and decreasing cost of exported products. According to optimum fitted pattern, import of "Soya" in importing product category should be increase 29 % and "Pistachio" production for export recommended to increase as 11 %. Recommended pattern for export results about 4015 million cubic meter saving each year.

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