Input-Output Multiobjective Optimization Approach for Food-Energy-Water Nexus

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Abstract: Food, energy and water are essential for human survival. These resources consume each other thus enhancing security in one resource can reduce security in another resource. Multiobjective optimization approaches have been used to understand the complexity associated with the Food, Energy Water (FEW) Nexus. However most of these approaches focus on either maximizing resource production or minimizing resource consumption in the FEW Nexus but not addressing the two simultaneously. To achieve sustainability of the FEW Nexus sustainable consumption and production of the resources need to be emphasized. In this paper, the Input-Output theory is used to develop a multiobjective optimization approach that minimises resource intensities. Minimising resource intensities results into minimised consumption and maximised production of resources in the nexus. Using the developed approach simulations are carried out to demonstrate its applicability in FEW Nexus. The results show that the approach can be used to explore alternative ways of minimizing consumption and maximizing production simultaneously based on the concept of non-dominated solutions.

1 INTRODUCTION

Sustainable consumption and production in Food, Energy and Water(FEW) nexus has a direct or indirect link in achieving many if not all of the Sustainable Development Goals developed by United Nations. Many countries are concerned about addressing Sustainable Development Goals in the midst of pressures emanating from rapid population growth and climate change. Climate change and the ever increasing population has led to increase in competition and trade-offs between food, energy and water (Bian & Liu, 2021). The FEW nexus approach is one that can be used to address the challenges of ever growing demand for food, energy and water (Miralles-Wilhelm & Muñoz, 2017). The nexus has become very important in addressing sustainability issues (Dalla Fontana et al., 2021).The nexus depicts some complex interactions with hidden feedback connections among food, energy and water resources.

The production of a specific resource requires the consumption of one or the two other resources thus playing a big role in determining the demand, supply and availability of the resources in the FEW Nexus (White et al., 2018). In relation to attaining global sustainability, managing the FEW Nexus has become a big challenge (Taniguchi et al., 2017). This is due to the fact that increasing security of one resource may have a negative consequence on another resource (Abdi et al., 2020).

To achieve sustainability in the FEW Nexus, resource consumption and production need to be optimized simultaneously and this may conflict each other (Okola et al., 2019). Multi-objective optimization approaches can be used to address conflicts in the FEW Nexus because they are known to deal with multiple conflicting objectives in real world problems. These approaches provide non-dominated solutions that identify trade-offs and synergies in FEW Nexus.

In a minimization problem a solution x_i is non-dominated as compared to x_j when each objective value of x_j is not less than that of x_i and at least one objective value of x_j is greater than x_i (Srinivas & Deb, 1994). Evolutionary algorithms have a great potential in solving multi-objective optimization problems. They evolve solutions in each generation thus being able to produce non-dominated solutions which are closer to the pareto-front. However, to the best of our knowledge there is no evidence of studies that have looked at how resource intensities in FEW

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Nexus can be minimised simultaneously using a multiobective optimisation approach

2 INPUT-OUTPUT THEORY IN FEW NEXUS

2.1 Input-Output Theory

The concept of a resource being consumed to produce another can be formulated using an Input-Output model that was designed and developed by Professor Wassily Leontief (Dietzenbacher & Lahr, 2004). Based on this theory, a resource sector is consumed by another sector and the final demand. For instance, the output of a resource sector is used to produce itself, other resources and for the domestic and industrial consumption. This is indicated by equation (1).

$$x_i = \sum_{j=1}^{n} x_{ij} + \sum_{j=1}^{m} y_{ij} \tag{1}$$

where x_i is the output of resource sector i, x_{ij} is the consumption of resource sector *i* to produce a resource sector *j*, and y_{ij} is the consumption of resource sector *i* to fulfil the final demand *j*.

The amount of resource sector *i* required to produce one unit of resource sector *j* is given as a fraction after dividing the amount consumed to produce a resource sector x_{ij} by the total output of a resource sector x_j. This fraction is expressed by equation (2).

$$a_{ij} = \frac{x_{ij}}{x_j} \text{ or } x_{ij} = a_{ij}x_j \tag{2}$$

Where a_{ij} is considered to be technological coefficient describing the amount of resource sector i consumed to produce a single unit of resource sector j.

Equation (1) and equation (2) can be combined in a matrix and a vector form using equation (3).

$$AX + Y = X \tag{3}$$

where A is a matrix of intensity or technological coefficients, Y is a vector of final demands, and X is a vector of outputs.

2.2 Resource Consumption and Production in FEW Nexus

The use of Input-Output theory in Food-Energy-Water Nexus has been demonstrated in (Karnib, 2016, 2017a, 2017b, 2018). In this nexus, there exists complex interactions where water is used to produce energy and food, energy is used to produce water and food and food can be used to produce energy. Therefore the consequences occurring in one sector affect the other sectors (Mahlknecht et al., 2020).

Consumption of resources in the FEW Nexus can be represented using variables as indicated in Table 1 below. The number of food resources can be denoted by q, energy resources by m and water resources by n (Karnib, 2018). The number of final demands can be denoted by h.

Table 1: Consumption of resources in the FEW Nexus.

Resource Consumption	Variable
The consumption of water i (w_i) to produce energy j (e_j)	w_ie_j
The consumption of water i (w_i) to produce food j (f_j)	w_if_j
The consumption of water i (w_i) by demand j (d_j)	w_id_j
The consumption of energy i (e_i) to produce water j (w_j)	e_iw_j
The consumption of energy i (e_i) to produce food j (f_j)	e_if_j
The consumption of energy i (e_i) to produce energy j (e_j)	e_ie_j
The consumption of energy i (e_i) by demand j (d_j)	e_id_j
The consumption of food i (f_i) to produce energy j (e_j)	f_ie_j
The consumption of food i (f_i) to produce food j (f_j)	f_if_j
The consumption of food i (f_i) by demand j (d_j)	f_id_j

Using equation (1), resource consumption and production in FEW Nexus can be formulated as equations (4),(5) and (6).

$$\sum_{j=1}^{m} w_ie_j + \sum_{j=1}^{q} w_if_j + \sum_{j=1}^{h} w_id_j = w_i \quad \text{where i=1, 2, ...,n} \tag{4}$$

$$\sum_{j=1}^{n} e_iw_j + \sum_{j=1}^{m} e_ie_j + \sum_{j=1}^{q} e_if_j + \sum_{j=1}^{h} e_id_j = e_i \quad \text{where i=1, 2, ...,m} \tag{5}$$

$$\sum_{j=1}^{m} f_ie_j + \sum_{j=1}^{q} f_if_j + \sum_{j=1}^{h} f_id_j = f_i \quad \text{where i=1, 2, ...,q} \tag{6}$$

The total resource consumptions can be represented using equation 7, 8 and 9.

$$\sum_{i=1}^{n} w_i = w \quad (7)$$

$$\sum_{i=1}^{m} e_i = e \quad (8)$$

$$\sum_{i=1}^{q} f_i = f \quad (9)$$

Equations 10 to 14 represent the resource consumption in production of other resources.

$$\sum_{i=1}^{n} \sum_{j=1}^{m} w_i e_j = we \quad (10)$$

Where ***we*** is the amount of water used to produce energy.

$$\sum_{i=1}^{n} \sum_{j=1}^{q} w_i f_j = wf \quad (11)$$

Where ***wf*** is the amount of water used to produce food.

$$\sum_{i=1}^{m} \sum_{j=1}^{n} e_i w_j = ew \quad (12)$$

Where ***ew*** is the amount of energy used to produce water.

$$\sum_{m=1}^{m} \sum_{j=1}^{q} e_i f_j = ef \quad (13)$$

Where ***ef*** is the amount of energy used to produce food.

$$\sum_{i=1}^{q} \sum_{j=1}^{m} f_i e_j = fe \quad (14)$$

Where ***fe*** is the amount of food used to produce energy.

2.3 Formulation of Objective Functions

The main objective is to minimise the amount of a resource used to produce another resource and at the same time maximising the production of the other resource. This is achieved by using technological coefficient specified by equation 2. Therefore, minimisation of the intensities implies minimising consumption as well as maximising production simultaneously. By combining equations 7 to 14, objective functions are formulated using equations 15 to 19.

$$MIN\ we/e \quad (15)$$

$$MIN\ wf/f \quad (16)$$

$$MIN\ ew/w \quad (17)$$

$$MIN\ ef/f \quad (18)$$

$$MIN\ fe/e \quad (19)$$

3 SIMULATIONS

Simulations were performed using gamultiobj which is a NSGA-II (Deb et al., 2002) based Multiobjective Genetic Algorithm function implemented in MATLAB. This function is a controlled elitist algorithm that prefers solutions with better fitness values and those that have low fitness values but they increase diversity of the population. Two simulations were performed using Business As Usual(BAU) resource consumption data obtained from the work of Karnib (Karnib, 2018) to demonstrate the feasibility of Multiobjective Optimization Algorithms in FEW Nexus.

A fitness function that takes a row vector of a given number of decision variables was specified. The objective functions formulated in section 2.3 were incorporated in this fitness function that returns a vector of objective function values. The fitness function was executed using gamultiobj with the specified lower and upper bounds of the given problem.

At first, based on BAU consumption data, resource intensities were calculated using equations 15 to 19. Then simulations are done to provide results of optimisation. The obtained results are used as a basis of comparison of resource intensities based on BAU values and the resource intensities obtained after optimisations. The comparisons were done to establish whether the resource intensities are reducing despite the consumption values increasing. Reduction in intensities is an indication of two scenarios. The first one is when there is simultaneous reduction in a resource used to produce another resource and an increase of the resource being produced. The second one is when the amount of change in consumption is small while the amount of change in production of a resource is large.

In the first simulation, the low bound vector of our fitness function is set to the BAU consumption values for both intersectoral and final demand values while the upper bound vector is set such that the intersectoral values do not have any upper limit while the final demand values are set to BAU values thus making the final demand to be fixed. This is to make the demand values constant. The purpose of these settings is to demonstrate the behaviour of the FEW Nexus when the demand is fixed but the intersectoral consumption changes while minimising the resource consumption intensities.

In the second simulation, the aim was to find out the behaviour of the FEW Nexus when both intersectoral consumption and the demand of the resources are changing while minimising resource intensities. In this case the lower bound and upper bound vectors for intersectoral consumption values are set to BAU and infinity values respectively. Similarly, the lower bound for final demand is set to BAU values while the upper bound is set to infinity values.

The Multiobjective Genetic Algorithm function was executed with the above settings and multiple non dominating solutions were obtained. From these many solutions we selected separately only those that indicated the minimum intensity values for consumption related to water for energy, water for food, energy for water, energy for food and food for energy.

4 RESULTS

The simulations carried out highlighted the potential of using Multiobective Optimisation Algorithms in understanding resource consumption and production in FEW Nexus. The algorithm generated many non-dominated solutions depicting various alternatives that can be taken by the decision maker. Only five solutions were selected for demonstration purposes. Each selected solution represented a scenario where a resource intensity was having the minimum value as compared to the same resource intensity values appearing in other solutions generated by the algorithm. Therefore, we selected five solutions such that the water-energy, water-food, energy-water, energy-food and food-energy intensities were the lowest respectively.

The values entered in Table 2 and Table 3 are obtained by subtracting the BAU intensity values from the ones obtained after the optimisation process. A negative value indicates a downward tendency of a resource intensity while a positive value indicates an upward tendency of a resource intensity. Based on these results, we can argue that although the amount of some resources consumed can be above the BAU values, it is still possible to achieve a reduction of minimised resource intensities.

Table 1 summarises the results from the first simulation. It is important to note that the water-energy resource intensities in all the solutions have higher values than the ones obtained from the BAU values. The first row shows the intensities for the solution where the water-energy intensity has the lowest value.

In this row there is an upward tendency for the water-energy, water-food and energy-food intensities while energy-water and food-energy intensities show a downward tendency. The second row is where the water-food intensity is the lowest. In this case water –energy and food-energy intensities have an upward tendency while water –food, energy –water and energy –food intensities have a downward tendency. In the third row, water-energy, water-food and energy-food intensities have an upward tendency while energy-water and food-energy intensities have a downward tendency. This is a row showing intensities for a solution that has the lowest value for energy-water intensity. The fourth row is the solution where there is the lowest energy-food intensity. In this row there is upward tendencies in water-energy and food-energy intensities while downward tendencies are observed in water-food, energy-water and energy-food intensities. In the last row where the food-energy intensity is the lowest, the water-energy, water-food, energy-water, energy-food have upward tendencies while food-energy having a downward tendency.

Table 2: The differences between BAU and Optimisation values from the 1st simulation.

Min. Intensity	Water-Energy	Water-Food	Energy-Water	Energy-Food	Food-Energy
Water-Energy	0.001	4.5E-05	**-0.0003**	1.35E-05	**-2E-06**
Water-Food	0.001	**-8E-07**	**-0.00043**	**-4.4E-07**	2E-06
Energy-Water	0.001	0.00012	**-0.00053**	2.08E-16	**-4E-17**
Energy-Food	0.001	**-8E-07**	**-0.00043**	**-4.4E-07**	2E-06
Food-Energy	0.012	0.03659	0.08569	0.037289	**-0.002**

Table 3: The differences between BAU and Optimisation values from the 2nd simulation.

Min. Intensity	Water-Energy	Water-Food	Energy-Water	Energy-Food	Food-Energy
Water-Energy	0.000968	0.000724	0.000131	0.00043	9.05E-06
Water-Food	0.001013	**-0.00013**	**-0.00046**	**-5.8E-05**	8.83E-06
Energy-Water	0.003376	0.006689	**-0.00372**	0.002054	3.91E-06
Energy-Food	0.001071	**-1.9E-05**	**-3E-05**	**-8.5E-05**	**-5E-06**
Food-Energy	0.011439	0.020998	0.071247	0.028517	**-0.00226**

Table 2 summarises the results from the second simulation. The first row indicates the solution where the water-energy intensity is the lowest. This row indicates an upward tendency for all the resource intensities. In the second row, the solution is where the water-food intensity is the lowest. In this case just like in the first simulation, the water –energy and food-energy intensities have an upward tendency while water –food, energy –water and energy –food intensities have a downward tendency. The third row shows intensities for a solution with the lowest value for energy-water intensity. In this row, it is only the energy-water intensity that has a downward tendency as the others have upward tendencies. The solution presented in the fourth row is the one with the lowest energy-food intensity. In this row the upward tendency is indicated only in water-energy intensity while other resource intensities show downward trends. The fifth row represents intensities for a solution where the food-energy intensity has the lowest value. In this row only the food-energy intensity has a downward tendency.

5 DISCUSSION

The findings from the simulations indicate that after the intensity minimisation process, there are those resource intensities that will have upward tendencies while others will have downward tendencies from the BAU values. It is also noted that water-energy intensity always has an upward tendency.

The Input-Output theory has the assumption that the total amount of a resource produced is the amount consumed by other resources. Therefore, the upward tendency of a resource intensity means a more increase in a resource consumption to produce another resource as compared to the resource produced.

The increase in water-energy intensity as compared to BAU in all cases is an indication that water is heavily consumed. This implies more water is used to produce energy and food as well meeting the final demand. The intensity value has increased because the rate of change of water consumption is more than that of energy production.

An increase in water-food intensity implies more water is available for food. The water-food intensity increases because there is an increase of water consumption rate as compared to food production rate. Also energy-water intensity has reduced because the water production rate has increased as compared to the rate of energy consumption.

Also it is noted that reduction in energy-water intensity implies water-energy, water-food and energy food intensities can increase while food-energy intensity can reduce. Water-energy and food-energy intensities can increase while water-food and energy-food intensities can reduce. There is also a case where water-energy, water-food and energy-food intensities can increase while food-energy intensity can reduce.

6 CONCLUSION AND FURTHER WORK

The proposed approach can support various alternatives of optimization of resource consumption and production in the FEW Nexus. The results show that when the resource intensities are minimized simultaneously, the consumption of water to produce energy will always be high. However, the consumption of energy and food to produce other resources maybe increase or reduce. Most existing approaches are not able to demonstrate ways of how to minimize the resource intensities simultaneously therefore making this approach a novel one. The design and development of a novel Many-Objective Optimization algorithm that is suitable to handle five or more objectives is considered as future work.

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