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A hierarchical Food-Energy-Water Nexus (FEW-N) decision-making approach for Land Use Optimization

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Abstract

The land use allocation problem is an important issue for a sustainable development. Land use optimization can have a profound influence on the provisions of interconnected elements that strongly rely on the same land resources, such as food, energy, and water. However, a major challenge in land use optimization arises from the multiple stakeholders and their differing, and often conflicting, objectives. Industries, agricultural producers and developers are mainly concerned with profits and costs, while government agents are concerned with a host of economic, environmental and sustainability factors. In this work, we developed a hierarchical FEW-N approach to tackle the problem of land use optimization and facilitate decision making to decrease the competition for resources and significantly contribute to the sustainable development of the land. We formulate the problem as a Stackelberg duopoly game, a sequential game with two players – a leader and a follower (Stackelberg, 2011). The government agents are treated as the leader (with the objective to minimize the competition between the FEW-N), and the agricultural producers and land developers as the followers (with the objective to maximize their profit). This formulation results into a bi-level mixed-integer programming problem that is solved using a novel bi-level optimization algorithm through ARGONAUT. ARGONAUT is a hybrid optimization framework which is tailored to solve high- dimensional constrained grey-box optimization problems via connecting surrogate model identification and deterministic global optimization. Results show that our data-driven approach allows us to provide feasible solutions to complex bi-level problems, which are essentially very difficult to solve deterministically.

Keywords

Food-Energy-Water Nexus; Bi-level Optimization; Land Use Optimization; Data-Driven Optimization

1. Introduction

A combination of rapid population growth, urbanisation, and economic development has spurred an overwhelming increase in world demands for food, energy, and water. With the availability of those goods being constantly decreasing, it is essential, now more than ever, to tackle effectively this issue.

This phenomenon can be linked to an economic theory called “The tragedy of the commons” (Lloyd, 1833), that refers to a situation within a shared resource system where individual users acting independently according to their own self-interest behave contrary to the common good of all users by depleting or spoiling that resource through their collective action (Hardin, 1968). Water, energy and food can be regarded as common resources, that can be overused and under-maintained. To add to the complexity, water, energy and food are interconnected resources forming what we referred to as Food-Energy-Water Nexus. For example, to produce food we need energy in the form of fertilizers or electricity, and water for irrigation. To produce clean water, we need energy for cleaning, and to produce energy we need water for cooling, and food if we were to use biofuels.

Even though we know that a holistic approach is required to tackle the problem of FEW increasing demand, the objectives of individual companies or organizations are usually based on short term profit.

To tackle this issue, Ostrom, E., 1990 discussed that enabling governments at multiple scales to interact with community organizations so that we have a complex nested system can give solutions to ‘the tragedy of commons’ problem. In other words, governments can shape strategies that lead organizations into actions that would avoid or limit stresses on the FEW Nexus. This can be done through rules and regulations, or subsidies that drive the objective and actions of the individual organizations towards the common good. This leads to a hierarchical system, with the government deciding (at the highest decision level) the rules, regulations and subsidies to motivate organizations towards deciding on their actions (at a lower decision level) to achieve the government’s objective, i.e. best sustainable long-term FEW-N solution.

In this work, we attempt to model and solve hierarchical systems as the one described above. We are focusing on the case of land use allocation which is an important issue for sustainable development and its optimization can have a profound influence on the provisions of interconnected elements that strongly rely on the same land resources, such as food, energy, and water. In Section 2 the Land Use allocation case study is explained and the hierarchical model is developed and presented. In Section 3 a novel data-driven algorithm for the solution of the complex hierarchical problem is presented, while the solution for land use problem is presented in Section 4. Section 5 concludes this paper.

2. Land Use Allocation Problem

The chosen case study is a land use allocation problem that involves a fictional piece of land owned by an organization. The organization will invest in this land, and may choose different types of developments, which can involve a mixture of both agricultural and energy

production land processes, consisting of solar energy, wind energy, fruit production, vegetable production, and livestock grazing. The interest of the land developer is to maximize its profit, while the interest of the government that rules this piece of land is to minimize the stresses on the FEW-N. This leads to a hierarchical optimization problem.

We are formulating this problem as a Stackelberg duopoly game (Stackelberg, 2011), a sequential game with two players – a leader and a follower. The government agents are treated as the leader, and the land developer as the follower. The formulation of this problem as a bi-level problem is presented in Eq. (1).

$$\begin{aligned}
 &\min \text{ FEW Nexus Stress} \\
 &s.t. \text{ Government Budget} \\
 &\max \text{ Developer's Profit} \\
 &s.t. \text{ Land Properties, Developers Budget, Land Process Models}
 \end{aligned} \tag{1}$$

2.1. Government's Optimization Problem – Leader's Problem

As mentioned before the government's move is only constrained by its budget. The objective of the government is to limit the stresses between food energy and water. While the importance of the FEW-N has been widely accepted, a quantitative index assessing the integrated FEW-N performance is rather lacking (Garcia et al. 2016). In this work, we have defined a FEW-N metric that aggregates FEW elements into a single 'geometric' metric, that can be used by the government as an objective.

The metric system involves scaling the quantitative value for each FEW element, to values between 0 and 1. A value of 0 indicates the worst possible scenario for a given element while a value of 1 implies the converse. The bounds on each element were determined by minimizing and maximizing the Land use allocation problem with each element as an objective. The three scaled elements are then used to create the geometric shape illustrated in Fig. 1. The area of the triangle formed corresponds to the FEW metric, the bigger the area the better the FEW Nexus solution.

$$\begin{aligned}
 FEW_{metric} = & \left[\frac{E_{total} - E_{min}}{E_{max} - E_{min}} \times \left(1 - \frac{W_{total} - W_{min}}{W_{max} - W_{min}} \right) + \frac{E_{total} - E_{min}}{E_{max} - E_{min}} \right. \\
 & \times \left. \frac{F_{total} - F_{min}}{F_{max} - F_{min}} + \left(1 - \frac{W_{total} - W_{min}}{W_{max} - W_{min}} \right) \times \frac{F_{total} - F_{min}}{F_{max} - F_{min}} \right] \frac{\sin 120}{2}
 \end{aligned} \tag{2}$$

where E_{total} , F_{total} are the total energy and food produced by the system correspondingly and W_{total} is the total water consumed by the system. E_{min} and F_{min} are the minimum amount of energy and food that can be produced, and W_{min} is the minimum amount of water that can be consumed. The same follows for E_{max} , F_{max} , and W_{max} .

For this case study, the government is using subsidies for each FEW sector. Therefore, the optimization problem of the government is as follows:

$$\begin{aligned} \max_{sub} \quad & FEW_{metric} \\ s.t. \quad & sub_X \leq bg \quad \forall x = E, F, W \end{aligned} \quad (3)$$

where sub_F , sub_E , and sub_W are the amount of dollars the government is subsidizing food, energy and water respectively.

2.2. Land Developer's Optimization Problem – Follower's Problem

As mentioned before the objective of the land developer is to maximize its profit. To achieve this, the land developer must take into account the characteristics of i) each land process, ii) the land itself, and iii) the subsidies given by the government. The specific case study for this work, assumes a fairly small piece of land in a climate similar to that of Texas, split into 8 evenly sized square plots, each with different properties. These properties, shown below in Table 1, define the limitations on which land processes can occur on each plot, and thus portray the specific situation of the assumed land developer.

Also, seasonal differences in climate can greatly impact the characteristics of the land as a whole, and change the appeal of various processes. These seasonal differences contribute to changes in a) energy profit based on consumers' demands, b) cost of transporting water due to availability, c) efficiency of the different systems in different weathers, and d) minimum water requirements for crops (due to rainfall), which are all modeled in the process. Therefore, the model includes parameters for each season that reflect the variations in energy and crop production efficiency, demand for energy, water cost, and water availability during different periods of the year.

For agricultural processes, the amount of water and energy used for the agricultural processes determines their yield (Table 2). The amount of Energy produced by solar and wind are only varied by land properties and seasonal changes. When both land properties and seasonal changes are at their optimal the amount of energy produced by one land piece is 50kW and the amount of energy produced by wind turbines is 1000kW. The profit gained from agricultural processes is proportional to the yield, whereas the profit from the energy processes is proportional to the kW produced.

The model also allows wind energy and agricultural processes to be developed on the same piece of land.

The model was developed in GAMS and it consisted of 1,723 equations, 216 integer variables and 1,107 continuous variables. The detailed model can be provided upon request as it was excluded from the document due to page restrictions.

3. Solution Method: ARGONAUT

A novel data-driven solution algorithm was developed for the solution of the large scale bi-level mixed-integer programming problem. The main idea behind the algorithm is to approximate the bi-level problem into a single level problem by collecting data from the

optimality of the lower level problem. The main steps of the proposed algorithm are illustrated in Fig. 2.

3.1. Data-Driven Solution Method

The proposed algorithm is tested with different constrained data-driven optimization strategies, and AlgoRithms for Global Optimization of coNstrAined grey-box compUTational problems (ARGONAUT) (Boukouvala et al., Boukouvala and Floudas, 2017) was chosen for the solution of the hierarchical FEW Nexus problem. The selection of solver was based on its ability to perform constrained optimization on black/grey-box problems with a global optimization strategy. The ARGONAUT algorithm performs global optimization on general constrained grey-box problems by providing accurate surrogate formulations to each unknown equation while incorporating adaptive parallel sampling, bounds tightening and variable selection within the algorithm for improved accuracy in obtaining the global solution.

3.2. Benchmarking

This algorithm was tested by solving the challenging set of bi-level test problems from Mitsos et al. 2017. The developed algorithm was able to converge to the global solution for 72% of the test problems, and was able to find feasible local solution for the rest of problems.

4. Results and Discussion

Using ARGONAUT as the data-driven solution method the results in Table 3 were attained. It is observed that different government strategies are able to give the same upper level objective with the same land development solution (Fig. 3). One can choose the strategy that poses the lowest expenditure for the government, i.e. Run 10. It is worth noting that without any governmental subsidies the FEW metric would have been 20.4% less than the optimal calculated with the subsidies, and with solar energy being developed in sections 7 and 8 instead of fruit production.

5. Conclusions

It is evident that the developed model and approach constitutes a greatly effective means of optimizing land use through a Food-Energy-Water Nexus approach. The flexibility, robustness and scalability of the model facilitates its application to a real-life case study, with the various parameters and variables being redefined to fit the desired situation, and the solutions made to fit a client's demands. This strong adaptability to real world situations can thus help create more sustainable methods of agriculture and energy production in a world where demands for resources are constantly increasing, whether this be on a local, regional or national scale.

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Figure 1.
FEW metric

Figure 2.
Illustration of the main steps of the Data-Driven Bi-level algorithm

1. Wind & Fruits	2. Wind & Fruits	3. Wind & Fruits	4. Wind & Fruits
5. Wind	6. Wind	7. Fruits	8. Fruits

Figure 3.
Land allocation solution

Table 1

Land Properties

	Land Section Number							
	1	2	3	4	5	6	7	8
Good soil					×	×		
Adequate sun	×	×						
Adequate wind							×	×
Water available	×	×	×	×			×	

Table 2

Yield of agricultural processes

Agricultural land use type	Yield (tonnes)
Fruits	$10E + 10^{-4}W$
Vegetables	$10E + 15^{-4}W$
Livestock	$E + 40^{-4}W$

Table 3

ARGONAUT solutions

Run#	FEW metric	# of Samples	Subsidies (k\$)					Total Subsidies(k\$)
			Solar	Wind	Fruits	Veg.	Liv.	
1	1.2299	147	0	19,796.2	50,000	0	0	418,777.2
2	1.2299	140	0	50,000.0	50,000	0	0	600,000.0
3	1.2299	234	0	20,363.5	49,811	0	0	421,047.0
4	1.2299	103	0	49,366.4	35,193.9	0	0	507,361.8
5	1.2299	161	0	0	50,000	0	0	300,000.0
6	1.2299	112	0	50,000	50,000	0	0	600,000.0
7	1.2299	288	0	50,000	21,847.1	0	0	431,082.6
8	1.2299	115	0	4,2368.1	50,000	0	0	554,208.0
9	1.2299	255	0	993.7	50,000	0	0	305,962.2
10	1.2299	267	0	8,218.2	25,533.9	0	0	202,512.6