Artificial Intelligence for Agricultural and Economic Planning

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Artificial Intelligence for Agricultural and Economic Planning (Extended Abstract)

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Abstract. In this project, we will illustrate an application of AI methods for agricultural and economic planning. In the first step, we will first focus on the agriculture sector and create a system which determines the type of crop and cultivation area to the farmers based on their preferences. Next we will integrate industry to the economic planning and utilize input/output relationships across different sectors of the industry. The industrial planning problem determines the quantity of industrial products in each sector and also to compute the industrial demand for agricultural goods. We formulate agricultural and industrial planning as multi-objective constraint optimization problem and use Constraint Programming, Integer Programming, Answer Set Programming and heuristic algorithms for solution. Long-term objective of this project is to develop a computational economic system which can handle production, consumption, logistics in a single country as well as in the international economy.

1 Introduction

One remarkable success of Artificial Intelligence in the last decades is that it has found numerous applications in real-life multi-disciplinary research problems. In this project, we will illustrate an application of AI methods for agricultural and economic planning. Namely, we will employ constraint programming and heuristic algorithms for production planning and optimum allocation of resources in various sectors of the economy. Long-term objective of this project is to develop a computational economic system which can handle production, consumption, logistics in a single country as well as in the international economy.

In Economics and Computer Science literature, computational tools have been used in macroeconomics mainly for statistical estimation, equilibrium analysis, business cycles, game theory [2]; but not for economic systems or economic planning. This is mainly because economists consider market system as an an efficient mechanism for allocating resources and determining the equilibrium price and quantity [12]. One of the crucial assumption of the efficient market hypothesis is that each firm can accurately predict the consumers' demand and preference for its products in a decentralized, competitive economy. Another major problem for the firms is that they may not balance the aggregate demand in their sector. Indeed, the agriculture and industry sector may exhibit underproduction/ overproduction of some goods which may cause shortage/waste, high prices, and give harm to consumer or producer utility. Specific to agriculture, a recent report [1] states that nearly one-third of annual global food production is wasted or lost. One noticeable pattern in the agriculture sector is that if there is overproduction of a particular crop in a year, then its market price becomes very low. Consequently, the next year, many farmers cease to cultivate this crop, but this time underproduction occurs and the market price rises significantly. This cycle continues across several years and the fluctuations in the agricultural sector is quite prevalent. Moreover import and export of agricultural products may not happen immediately in the global market, they depend on availability of crops, currency exchange rate, prearrangement and transportation.

Another pressure on the agriculture sector is the global population growth which causes sustained rise in the food prices [1]. Thereby, another prominent issue is better utilization of farm area in all countries for sufficient international food supply. In North America, Russia, Asia there are many available uncultivated land but on the other side, rain forests in Africa are destroyed to open farm area.

The waste of products in the current market system is mainly because firms do not coordinate with each other and they give production decisions without any information from the consumer side. In the modern age, we should utilize communication and computer technology to organize producers and help them to balance demand and supply. In this respect, information sharing, coordination and planning will help producers to give better production decisions and resolve the the mismatch between demand and supply. This notion is relevant for agriculture, industry and other sectors in the economy.

In the computational economic systems project, we will first focus on the agriculture sector of a single country. We assume the annual aggregate demand for each crop is known create a system which assigns the type of crop and cultivation area to the farmers based on their preferences. The agricultural planning problem exhibits great challenges due to several factors such as climate of each region, minimum quotation limit, replantation, annual/perennial plants. Another major challenge is the scale of the problem: In a country with the order of 10^6 farmers and 10^2 crops, how to find an efficient method to achieve agricultural planning?

In the next step, we will integrate industry to the economic planning and expand the model to multiple sectors. We will utilize input/output relationships across different sectors of the industry, and now the planner will adjust the quantity of agricultural and industrial goods to match the demand from the consumers and exports. Therefore, incorporating multiple sectors to planning will yield more accurate production decisions in agriculture and industry.

In the later steps of the project, we will integrate service, transportation and international trade to the system. Our aim is to construct a computational system which performs resource allocation, production planning, inventory management, handling logistics. By this project, we offer a long-run solution to sustainable development, optimum resource utilization and economic efficiency.

2 The Agricultural Planning Problem

The AP problem determines the crop type and cultivation area for each farmer in a particular year in order to satisfy farmer preferences as much as possible, subject to production constraints. We assume that the equilibrium price and the aggregate annual demand in the country for each type of crop is known and there is no fallowing. Formally, the input of the Agricultural Planning problem is $\mathcal{A} = (F, C, I, D, L, Y, P, B, M)$ where

- $F = [1, ..., f]$ is the set of farmers,
- $C = [1, ..., c]$ is the set of crops,
- $I = [y_1, ..., y_t]$ denotes the identity of perennial (multi-year) plants,
- $D = [(\overline{p}_1, \overline{v}_1, \overline{q}_1), ..., (\overline{p}_c, \overline{v}_c, \overline{q}_c)]$ denotes the price, production cost and the quantity demanded (annual) for each crop,
- $L = [l_1, ..., l_f]$ denotes the land area of each farmer,
- $Y = [[y_{1,1} ..., y_{1,t}], ..., [y_{f,1} ..., y_{f,t}]]$ denotes the existing land area for perennial plants of each farmer,
- $P = [P_1, ..., P_f]$ denotes the preference of each farmer among annual crops,
- $B = [[b_{1,1} ..., b_{1,c}], ..., [b_{f,1} ..., b_{f,c}]]$ denotes the productivity of each farmer (output per unit area for each crop), [1]
- $M = [m_1, ..., m_c]$ denotes the minimum cultivation area of a crop for a farmer.

The preference of a farmer $P_j = [\mathit{rank}_{j,1}, ..., \mathit{rank}_{j,c}]$ is a ranking of crops such that higher rank corresponds to higher preference. If the existing total land area of a prennial plant is greater (resp. lower) compared to its aggregate demand, then part of its land area should be converted to other type of crops (resp. its land area is increased).

The output of the AP problem is $[[n_{1,1} ..., n_{1,c}], ..., [n_{f,1} ..., n_{f,c}]]$ the land area that each farmer cultivates for each type of crop. Then $Q_{j,i} = n_{j,i}.b_{j,i}$ is the amount of annual production of crop i by farmer j, and $Q_i = \sum_{j \in F} Q_{j,i}$ is the aggregate production of crop i. The objective of the problem is to assign land area for crops to each farmer in order to minimize the imports, maximize the exports from excess production and satisfy the farmers' preferences. The priority (importance) of these optimization objectives are in the above order, from highest priority to lowest. Namely, the objective is

$$\mathit{minimize} \quad \sum_{i \in C} \overline{p}_i.\mathit{Imp}_i$$

$$\mathit{maximize} \quad \sum_{i \in C} (\overline{p}_i - \overline{v}_i).\mathit{Exp}_i$$

$$\mathit{maximize} \quad \sum_{j \in F} \mathit{Utility}_j$$

subject to $n_{j,i} \geq m_i$ and $\sum_{i \in C} n_{j,i} \leq l_j$, for $1 \leq i \leq c, 1 \leq j \leq f$.

$\mathit{Utility}_j = \sum_{i \in C} \mathit{rank}_{j,i}.n_{j,i}$ denotes the preference satisfaction degree of the farmer j. The quantity of import and export of a crop are calculated by

$$\mathit{Imp}_i = \begin{cases} 0 & \text{if } Q_i \geq \overline{q}_i \\ \overline{q}_i - Q_i & \text{if } Q_i < \overline{q}_i \end{cases}$$

$$\mathit{Exp}_i = \begin{cases} 0 & \text{if } Q_i \leq \overline{q}_i \\ Q_i - \overline{q}_i & \text{if } Q_i > \overline{q}_i \end{cases}$$

[1] If the soil or climate does not allow cultivation of a crop, then productivity is set to zero

Essentially, the goal of the AP problem is first to fulfill the local demand as much as possible for self-sufficiency and then maximize the profit from exports and maximize the farmers' utility. Note that in the economy-wide level, it may not be possible to find an optimum solution to the above agricultural planning problem in an acceptable amount of time. Therefore we should develop efficient and approximate methods. One alternative is the divide-and-conquer approach: We will divide the problem into two levels, the region level and the farmer level. For the region level problem, we partition the country into regions such that the climate and productivity are homogenous within a region. Our approximation method first divides the aggregate quantity of crops across regions; and then divides the regional production between farmers inside the region.

Formally, the input of the region-level agricultural planning problem (RAP) is $\mathcal{R} = (C, R, S, I, Z, D, E, M)$ where C, I, D are the same as in the original AP problem, and

- $R = [1, ..., r]$ is the set of regions,
- $S = [s_1, ..., s_r]$ denotes the cultivable farm area in each region,
- $Z = [[z_{1,1} ..., z_{1,t}], ..., [z_{r,1} ..., z_{r,t}]]$ denotes the existing farm area for perennial plants in each region,
- $E = [[e_{1,1} ..., e_{1,c}], ..., [e_{r,1} ..., e_{r,c}]]$ denotes the productivity for each crop in a region,
- $M = [m_1, ..., m_c]$ denotes the minimum cultivation area for each crop in a region (for logistics reasons).

The output of the RAP problem is $[[n_{1,1} ..., n_{1,c}], ..., [n_{r,1} ..., n_{r,c}]]$ the cultivation area of each type of crop, in each region. Then $Q_{k,i} = n_{k,i}.e_{k,i}$ is the amount of production of crop i in a region k. As before, the objective is to minimize the cost of imports and maximize the revenue from exports:

$$\mathit{minimize} \quad \sum_{i \in C} \overline{p}_i.\mathit{Imp}_i$$

$$\mathit{maximize} \quad \sum_{i \in C} (\overline{p}_i - \overline{v}_i).\mathit{Exp}_i$$

subject to $n_{k,i} \geq m_i$ and $\sum_{i \in C} n_{k,i} \leq s_k$, for $1 \leq i \leq c, 1 \leq k \leq r$.

The second level problem (farmer level) problem divides the regional production (computed in the first level) among farmers. Namely, each farmer is assigned a cultivation area such that the total cultivation area of the region for each type of crop is satisfied. Hence it is a simpler version of the original AP problem with less number of farmers and some factors such as productivity, profit are eliminated.

Formally, the farmer-level agricultural planning problem (FAP) is defined as $\mathcal{F} = (F, C, I, U, L, Y, P, M)$ where F, C, I, L, Y, P, M are the same as in the original AP problem, and $U = [u_1, ..., u_c]$ denotes the total farm area of each crop in the region (computed by RAP above). The output of the FAP problem is $[[n_{1,1} ..., n_{1,c}], ..., [n_{f,1} ..., n_{f,c}]]$ the cultivation area of each farmer and each type of crop which attains

$$\mathit{maximize} \quad \sum_{j \in F} \mathit{Utility}_j$$

subject to $n_{j,i} \geq m_i$, $\sum_{j \in F} n_{j,i} \geq u_i$, and $\sum_{i \in C} n_{j,i} \leq l_j$, for $1 \leq i \leq c, 1 \leq j \leq f$

Since the number of regions is much smaller than the number of farmers, the RAP problem is relatively easier to solve compared to the FAP problem. We can solve the region-level planning problem by Constraint Programming, Integer Programming or Answer Set Programming tools. For the farmer-level problem, we will utilize a heuristic algorithm: We will first assign every farmer his most preferred annual crop and keep his perennial plant area the same. In case a shortage or surplus of some crops in the region, the algorithm will switch land area for overproduced crops to underproduced crops, depending on the preference ordering of farmers.

Note that other levels can be added to the agricultural planning problem when desired, for example a three-level approximation method would have region-level, village-level and farmer level. More levels can enhance computational efficiency and also circumvent the issue of minimum production limit in a village.

3 Industrial and Multi-sector Planning

In the previous section, we only considered the agricultural products and assumed that the annual aggregate demand for crops in the country is exogenous and known. The demand for agricultural products comes from households (consumers) and industry. Now we will study the industrial planning problem to determine the quantity of industrial products in each sector and also to compute the industrial demand for agricultural goods. Once we find out the demand for crops from industry, we can sum this quantity with the household demand for agricultural goods and feed the total demand to the AP problem in the previous section, to find agricultural equilibrium.

Let $S = [1, ..., s]$ be the set of sectors in the industry. A sector consists of multiple competing firms. Each firm in the sector uses the same set of goods as input and produces one good as output. We identify a sector with its output product, thus S also shows the set of all industrial goods. $F = [[f_{1,1}..., f_{1,g_1}], ..., [f_{s,1}..., f_{s,g_s}]]$ denotes the firms operating in each sector, where g_j is the number of firms in sector j, $1 \leq j \leq s$. $H = [h_1, ..., h_s]$ denotes the total production capacity (per period) of each sector. Let $Q_{k,i}$ stand for the quantity of good i, produced by firm k.

We classify the goods as *final* and *intermediate* goods. Final goods are the goods that are directly purchased and used by the end users (consumers), e.g. banana, car, dishwasher, trouser. Intermediate goods are not directly purchased by consumers, they are used in the production sequence of final goods, e.g. fertilizer, chip, steering wheel. Note that some tpe of goods, like a speaker, can be used as both intermediate good and final good.

The Industrial Planning (IP) problem studies allocation of production between sectors and individual firms based on input-output dependencies and firms' characteristics (cost, capacity). As in agricultural planning, we divide the problem into two levels: Sector level and firm level. The upper level problem MSPP (Multi-sector planning problem) computes the sector-wide aggregate production of each good with respect to objective function and input-output relationships. The decision variables are $V = [Q_1, ..., Q_s]$ the aggregate quantity of each good to be produced in the country (including final and intermediate usage). Let T denote the set of linear equations that define the input/output relations between different sectors i.e. the industrial production technology. T specifies the type and quantity of goods to produce one unit of industrial good i. Note that the agricultural goods can show up as input in T, but not as output since production technology and constraints in agriculture are different. For the moment, we do not consider labor or wage in the production process. We assume that the market price and average production cost of each good $P = [(\overline{p}_1, \overline{v}_1), ..., (\overline{p}_s, \overline{v}_s)]$ are given. We also assume that the demand for final goods from the domestic consumers $D = [\overline{q}_1, ..., \overline{q}_d]$ and the international demand (export) for final and intermediate goods $O = [\overline{o}_1, ..., \overline{o}_s]$ are known. Then the MSPP problem $\mathcal{I}$ is defined as, given (S, F, H, T, P, D, O) as input, find the sectoral output i.e. the value of variables in V, to minimize imports and maximize exports

$$\textit{minimize} \quad \sum_{i \in S} \overline{p}_i.\textit{Imp}_i$$

$$\textit{maximize} \quad \sum_{i \in S} (\overline{p}_i - \overline{v}_i).\textit{Exp}_i$$

subject to input-output dependencies in T and $Q_i \leq h_i$, for $1 \leq i \leq s$.

The above MSPP determines the aggregate production of industrial goods in each sector. Then the firm-level planning problem (FPP) allocates the sector-wide production among the firms operating within the sector. A simple solution would be dividing the aggregate quantity linearly with respect to the firms' production capacity. Alternatively, more sophisticated optimization methods can be employed which take into account heterogeneous cost, quality, entrepreneurs' production target. Another option can be a decentralized market mechanism where the planning authority only announces aggregate sectoral quantity, and then each firm autonomously decides its own price and quantity.

4 Related Literature

In operational research literature, there are nation-wide agricultural crop planning models [3, 6, 11], however these models consider only single or several types of crops and do not take into account preferences of farmers. These papers mostly employ multi-objective optimization and study production planning, seasonal harvest scheduling, supply chain, retailers and transportation cost [13].

Industrial planning, as a theory, has been a primary concept of centrally planned economies. A seminal work on macroeconomic planning is Leontief's input-output tables for examining interdependencies between various sectors of the industry [7]. However USSR and other socialist economies have not used input-output analysis for planning; instead they have realized material-balance method which is based on counting available raw materials and forwarding to industry sectors [4, 5]. On the other side, policy makers in Western countries did not implement production planning, as they believe that the market economy is an efficient mechanism for allocating resources [8]. For macroeconomic and sectoral analysis, researchers have investigated GDP and national income accounting, impact of business cycles and shocks on sectors, estimating input-output coefficients, regional dependencies, energy and environmental factors, forecasting economic variables [9, 10, 14].

5 Conclusion

The agriculture and industry may occasionally encounter shortage or surplus of goods which causes waste or misallocation of resources. This is mainly because the producers (farmers and firms) operate idependently, and also they give production decisions with incomplete information from the consumer side. Due to population growth and scarcity of resources, one of the challenges of the humanity is finding ways of better utilization of resources and reducing waste.

The objective of this project is to develop a computational system which achieves macro-level planning for sectors in the economy. This system will be beneficial for coordinating producers to balance demand & supply, and optimize output. In the first step, we will focus on agriculture and address the production planning of crops to satisfy the aggregate annual demand. In the next steps, we will incorporate industry, service, logistics, international trade to the model. We will utilize constraint programming tools and heuristic algorithms to find efficient and optimal solution to the planning problems above. Our ultimate goal is to design and implement a computational economic system, a network which manages economic activities in the world.

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