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Agricultural Production Planning Using a Multicriteria Optimization Model

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Abstract:

Purpose: *This study aims to plan agricultural production on a real farm in Poland using an optimization model.*
Design/Methodology/Approach: *Factors, especially variable ones (the weather, economic conditions), make it difficult to plan production on a farm. It is not uncommon for a decision-maker to attempt at achieving several goals simultaneously. Solving such a problem is enabled by a linear-dynamic, multicriteria optimization model. In this study, the optimization criteria related to agricultural income are agricultural production, and organic matter losses in the soil. The empirical material consists of real data on a farm located in the West Pomeranian Voivodeship (Poland).*
Findings: *The solution of a multicriteria, linear-dynamic model has indicated a production structure that ensures correct crop rotation, timely performance of agrotechnical works, and meets the conditions for receiving EU subsidies. It also allowed the highest agricultural income and the largest production under given conditions to be obtained. In contrast, a positive balance of organic matter shows that the environment is not degraded.*
Practical Implications: *Linear-dynamic, multicriteria optimization models can be an effective tool supporting farm production planning.*
Originality/Value: *The model applied for this paper's needs is of high application value. It can be used for crop cultivation farms or mixed production farms for determining alternative plans.*

Keywords: *Agricultural income, agricultural production, soil organic matter balance, multi-criteria optimization model.*

JEL code: *C44, D61.*

Paper type: *Case Study.*

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1. Introduction

Due to its biological nature, agricultural production is significantly different from production in the industry (based on mechanical and chemical processes). Constant factors shape it at the farm level, such as the area used for agriculture, owned agricultural tools and machines, labor force, and variable resources. Variable factors that hinder production planning include sowing structure, weather conditions, the prices of means of production and services, the number of subsidies. Dynamic optimization programming is one method supporting farm decision making over several years (Bellman and Dreyfus, 1967; Bertsekas, 2017; Zaród 2018). Its tools in the form of optimization models determine the production structure that will yield the best economic effect under given conditions.

The literature on the subject contains examples of the use of optimization models in various economy areas. For example, Galanc *et al.* (2016) used optimization models to support ICT decisions, Taghinezhad (2019) in food supply chain management, Madlener and Glensk (2013) in the energy industry to minimize costs and Maron and Maron (2019) on the financial market. In agricultural production, Juan *et al.* (1999) optimized the use of available water for vegetable irrigation around Salvatierra (Spain). Riesgo and Gomez-Limon (2006) also dealt with the problem of field irrigation. They built optimization models for farms in the Duero River valley in Spain. Also, Manos *et al.* (2013), using multi-criteria optimization models, studied agricultural production's sustainable development in the Thessalia region (Greece).

The optimal production plan developed by them provided a higher gross margin, lower fertilizer consumption, and lower irrigated water consumption. However, Rodriguez *et al.* (2009) used a linear stochastic programming model to plan pig farming. Cupała *et al.* (2015) optimized the equipment of the machine park in sustainable agriculture. The algorithms used enabled the selection of appropriate technical equipment and minimized the risk associated with its purchase. Sielska (2000), using multi-criteria programming (weighted criteria), presented various agricultural production scenarios, allowing the decision-maker to make a choice. Zieliński and Ziętara (2017) also attempted to determine the economic situation of farms specializing in the cultivation of cereals, oil, and protein plants using linear-dynamic optimization models.

This study's main purpose is to plan farm production on a real farm X using a linear-dynamic, multi-criteria optimization model. Its solution will indicate the production structure that will allow obtaining the highest agricultural income and the largest production under given conditions and will not degrade the natural environment.

2. The Characteristics of the Farm

Farm X is located in the West Pomeranian Voivodeship in the Nowogard commune. It has 118.89 ha of arable land and 225.11 ha of permanent grassland. Cereal crops (wheat, triticale, and barley), rapeseed, field beans, and honey crops are grown on the farm. Honey plants (phacelia, borage, melilot - grown alternately) cover 3.89 ha and are the source of nectar or honeydew for bees. The farm X deals only with plant production. Organic fertilization of crops was replaced by ploughing of straw and crop residues. Hay collected from 195 ha of grassland is transferred to a nearby fur farm. The rest of the meadows are subject to the Natura 2000 program, as there are protected species of plants and birds.

Two people work on the farm all year round. Additionally, one employee is employed during the harvest season. The necessary agricultural machines and tools enable the work to be performed. Table 1 summarizes the basic data on the agricultural holding in 2016-2019.

Table 1. *The characteristics of the farm*

Specification	2016	2017	2018	2019
Crop yields (dt/ha):				
Wheat	62,0	55,0	52,0	58,0
Rye	48,0	47,0	45,0	46,0
Triticale	52,0	50,0	48,0	51,0
Rapeseed	35,0	30,0	29.0	32,0
Field bean	40,0	38,0	37,0	36,0
Meadow	67,0	54,0	52,0	44,0
Prices (PLN/dt):				
Wheat	72,37	66,19	72,28	74,46
Rye	52,68	54,20	62,84	54,74
Triticale	61,65	59,14	67,92	59,21
Rapeseed	162,56	158,28	157,23	159,08
Field bean	90,00	82,00	98,00	110,0
Cultivation costs (PLN/ha):				
Wheat	3789,20	3560,50	3587,00	3630,50
Rye	2972,20	2985,20	2990,20	3050,80
Triticale	3572,40	3310,70	3306.40	3353,60
Rapeseed	4520,20	4450,86	4438,60	4470,70
Field bean	3502,80	3483,30	3527.30	3691,10
Meadow	2890,30	2750.40	2698.50	2782,40
Direct payments (uniform area payment and payment for greening in PLN / ha):				
Wheat, rye, triticale, rapeseed, field bean, meadow	772,15	771,32	767,37	788,18
Meadow in the Natura 2000 area	1683,15	1682,32	1678,37	1699,18
Field bean (plus a surcharge for legumes)	1202,64	1377,84	1488,41	1553,98

Source*: Own elaboration pursuant to: (Luter, 2017; ARMA, 2016-2019; Agricultural calculations, 2016-2019).*

These data will be used to determine the technical and economic parameters and the coefficients of the multi-criteria optimization model's goal criteria.

3. Research Methodology

The main research method is a dynamic, multicriteria optimization model. Its mathematical notation, adopted for plant agricultural production, has the following form (Krawiec, 1991):

$\boldsymbol{ax}(t) \leq \boldsymbol{b}(t)$ - restrictive conditions (1)

$\boldsymbol{x}(t+1) \leq \boldsymbol{x}(t) + f_t\,[\boldsymbol{x}(t), \boldsymbol{u}(t)]$ - dynamics conditions (2)

$F = max\,\{F_1, F_2,\, F_3\}$ - control criterion (3)

$\boldsymbol{x}(t) \geq 0,\ \ \boldsymbol{u}(t) \geq 0$ - boundary conditions (4)

where: t – states (subsequent years of farming), t = 1, ..., 4.

$\boldsymbol{a}$ – the vector of technical and economic parameters,
$\boldsymbol{b(t)}$ – the vector of restrictions in subsequent states
$\boldsymbol{x(t)}$ – state vector t,
$\boldsymbol{u(t)}$ – control vector,
$\boldsymbol{x(t+1)}$ – state vector in the year $t+1$

In the formula (1) there are state restrictions that apply to the area of arable land and grassland. The control vector $\boldsymbol{u(t)} = u_{ij}(t)$ shows flows within the farm or between the farm and the environment. The components of this vector describe the areas of successive plants at the transition of the farm from the state t to $t+1$. The indicators i, j determine the order of successive crops, e.g. after plant i, plant j will be grown.

The dynamics equations for plant production take the form:

$$x_{\boldsymbol{i}}(t+1) = \sum_p u_{pi}(t) \tag{5}$$

where: $x_i\,(t+1)$ – the area of i-th plant grown in the year $t+1$,
$u_{pi}(t)$ – the area of various fore crops p, followed by i-th plant in year t +1.

Goal criterion F_1 applies to gross agricultural income and is expressed by the formula:

$$F_1 = \sum_{t=1}^{4}[m(t)^T u(t) + w(t+1)^T x(t+1)] \to max \tag{6}$$

where: $\boldsymbol{m}(t)$, $\mathbf{w}(t+1)$ – the vector of unit income for state variables and controls denoting commodity activities.

F2 is a control criterion that maximizes the volume of commodity production in the form:

$$F_2 = \sum_{t=1}^{4}[g(t)^T u(t) + k(t+1)^T x(t+1)] \to max \quad (7)$$

where: ***g****(t),* ***k****(t +1)* – the vector of unit control variable yields (crops) and state in subsequent years.

Function F3 maximizes the amount of soil organic matter:

$$F_3 = \sum_{t=1}^{4}[o(t)^T u(t) + p(t+1)^T x(t+1)] \to max \quad (8)$$

where: o(t), p(t +1) – the vector of unit coefficients of soil reproduction or degradation for state variables and controls.

The multi-criteria, dynamic farm optimization model X will be solved using targeted programming (Charnes and Cooper, 1961; Szapiro 2001). In this approach, the built model should be solved separately for each criterion. After obtaining optimal results due to the control criteria, each objective function is treated as another limiting condition of the model in the form:

$$\boldsymbol{m}(t)^T \boldsymbol{u}(t) + \boldsymbol{w}(t+1)^T \boldsymbol{x}(t+1) = dr \quad (9)$$

$$\boldsymbol{g}(t)^T \boldsymbol{u}(t) + \boldsymbol{k}(t+1)^T \boldsymbol{x}(t+1) = pr \quad (10)$$

$$\boldsymbol{o}(t)^T \boldsymbol{u}(t) + \boldsymbol{p}(t+1)^T \boldsymbol{x}(t+1) = so \quad (11)$$

where: dr – the highest value of agricultural income obtained in the single- criterion model solution;
pr – the optimal volume of agricultural production obtained in the single-criterion model solution;
so – the amount of organic matter retained in the soil resulting from the optimal single-criteria model solutions.

Under all these conditions, there is a restrictive equality constraint that should be weakened. The full weakening of equality is the transformation in which the variables of deficiency (u-) or excess (u+) expressing non-compliance with the achieved values in single-criteria models occur. After the transformation, the additional restrictive conditions will take the form:

$$\boldsymbol{m}(t)^T \boldsymbol{u}(t) + \boldsymbol{w}(t+1)^T \boldsymbol{x}(t+1) - u_1^+ + u_2^- = dr \quad (12)$$

$$\boldsymbol{g}(t)^T \boldsymbol{u}(t) + \boldsymbol{k}(t+1)^T \boldsymbol{x}(t+1) - u_3^+ + u_4^- = pr \quad (13)$$

$$\boldsymbol{o}(t)^T \boldsymbol{u}(t) + \boldsymbol{p}(t+1)^T \boldsymbol{x}(t+1) - u_5^+ + u_6^- = so \quad (14)$$

Many criteria need to be replaced with one distance function describing the costs (penalties) of deviations from the target values. There will be both variables regarding the excess or shortage of agricultural income and agricultural production in this function, as no specific recommendations as to how to achieve them are assumed. However, the deficiency of soil organic matter should be minimized not to degrade the natural environment. The distance function will have the form:

$$F = u_1^+ + u_2^- + u_3^+ + u_4^- + u_6^- \rightarrow min \qquad (15)$$

4. Construction of a Multi-Criteria, Dynamic Optimization Model

The farm model X consists of four blocks (stages) corresponding to subsequent years of research. Each stage is a linear model, connected to the following one using binding conditions (dynamics). Binding conditions apply to crop rotation. Because the farm only deals with plant production. The proposed change that considers the phytosanitary requirements of crops and the timely performance of agrotechnical operations is presented in Table 2.

Table 2. *Plant succession in the studied years*

Years	Field			
	I	II	III	IV
2016	wheat	triticale, rye	rapeseed, field bean	phacelia
2017	triticale, rye	rapeseed, field bean	wheat	borage
2018	rapeseed, field bean	wheat	triticale, rye	melilot
2019	wheat	triticale, rye	rapeseed, field bean	phacelia

Source: *Own élaboration.*

Restrictive (state) conditions describe the structure of crops, labor intensity of crops, and the requirements of the Agency for Restructuring and Modernization (ARMA) of Agriculture. A farmer is entitled to a subsidy if in his agricultural production, there are at least three different crops, of which the main crop does not exceed 75% of the sown area, a minimum of 5% of crops meets the ecological conditions. Higher subsidies for legumes are due if the area of these crops does not exceed 75 ha. Also, the high soil requirements of wheat limit its cultivation area to 35% of the arable land area.

The built model consists of 40 state and control variables, 60 limiting conditions and dynamics, and 3 goals functions. The first goal function maximizes gross agricultural income. Its coefficients are revenues from individual crops together with subsidies fewer than production costs. Sometimes, in the analyzed years, the production costs exceeded the revenues, and the subsidies decided on a given crop's profitability. In the case of honey plants and permanent grasslands, subsidies are parameters of this goal function. The amount of honey obtained covers the costs of growing honey plants, and the income from the production of hay is equal to its production costs. The crops of commodity plants are parameters of the second goal function. Obtaining the largest production effects is associated with satisfying the growing needs of society and the industry's raw material needs. On the other hand, the amount of organic matter supplied or taken from the soil by individual crops creates the third goal function's coefficients. According to Eich and Kindler, these coefficients were determined based on the indicators of soil substance reproduction and degradation (Kopiński and Kuś, 2011). This function should also be maximized so as not to degrade the natural environment.

5. Research Results

The farm production structure resulting from the dynamic model's solutions separately due to each single criterion was similar. The differences concerned permanent grassland, which was not commercial production and did not enter the model's solution with a second goal function. In the model's solution with the third purpose function, the rye replaced triticale because it produces a larger straw and thus supplied more organic matter to the soil. The results of the multi-criteria model solution are presented in Table 3.

***Table 3**. Solution of a multi-criteria farm model*

Specification	Years			
	2016	2017	2018	2019
Arable land (ha)	118,89	118,89	118,89	118,98
Wheat (ha)	35,67	37,72	41,61	35,67
Triticale (ha)	41,61	35,67	37,72	41,61
Rye (ha)	0,00	0,00	0,00	0,00
Rapeseed (ha)	23,78	23,78	21,40	23,45
Field bean (ha)	13,95	17,83	14,27	14,28
Honey plants (ha)	3,89	3,89	3,89	3,89
Natura 2000 meadow (ha)	30,11	30,11	30,11	30,11
Meadow (ha)	195,00	195,00	195,00	195,00
Agricultural income (PLN)	319486,19	294505,93	311086,00	338524,49
Agricultural production (dt)	5772,99	5256,95	5130,79	5462,93
Soil organic matter (t)	347,75	337,23	329,18	339,15

***Source:** Own calculations using Mathlab.*

The production structure resulting from the multi-criteria, dynamic model solution meets all the Agency for Restructuring and Modernization of Agriculture requirements. It provides timely performance of agrotechnical works and proper soil coverage with vegetation. Plant succession (Table 4) creates good phytosanitary conditions for crops (e.g., rapeseed and field beans are good for the crop for wheat, while triticale and rye can cause many diseases lowering wheat yield).

Table 4. *Alternating crops in the analyzed years*

Years	Field			
	I	II	III	IV
2016	wheat 35,67ha	triticale 41,61ha, rye -	rapeseed 23,78ha, field bean 13,95ha	phacelia 3,89ha
2017	triticale 35,67ha, rye -	rapeseed 23,78ha, field bean 17,83ha	wheat 37,72ha	borage 3,89ha
2018	rapeseed 14,27ha field bean 14,27ha	wheat 41,61ha	triticale 37,72ha, rye -	melilot 3,89ha
2019	wheat 35,67ha	triticale 41,61ha, rye -	rapeseed 23,44ha, field bean 14,28ha	phacelia 3,89ha

Source: *Own elaboration.*

Agricultural income obtained within 4 years from this production structure amounts to PLN 1263602.61. EU subsidies largely determined its amount. The products produced on the farm in the analyzed years (21623,66dt) do not contain permanent grassland harvests and honey plants. Favorable agro-climatic conditions contributed to the increase in crops in 2016. Cereal plants and oilseed rape degrade the soil.

However, their plowed straw provides large amounts of organic matter to the soil. After introducing straw into the soil, microorganisms intensively multiply (Spiak and Piszcz, 2001). To prevent this, nitrogen must be supplied to the soil, which will help break down the straw faster and more efficiently. Field bean is a legume that reproduces soil. Too much organic matter in the soil is also undesirable. It may cause groundwater and surface water pollution with biogens (Smagacz, 2000). 980kg of soil humus (1353.31t / 4 / 344ha = 0.98t/ha) obtained on average per 1 ha of farmland per year in an optimal solution that will not pollute water will have a positive impact on the natural environment.

6. Conclusion

To summarize we present the following conclusions:

1. Linear-dynamic, multi-criteria optimization models can be an effective tool supporting farm production planning.
2. The production structure resulting from the solution of a farm ensures correct crop rotation, timely performance of agrotechnical works, and meets the conditions for receiving EU subsidies.
3. Gross agricultural income in the analyzed years depended largely on direct payments and additional payments.
4. Plowing of straw and crop residues ensured a positive balance of organic matter in the farm soils at a level that does not degrade the natural environment.

References:

Agricultural calculations. 2016-2019. Retrieved from: https://zodr.pl/download/ekonomia/kalkulacje_roslinne.pdf.

Agency for Restructuring and Modernization of Agriculture (ARMA). 2016-2019. Direct payments and payments under the RDP 2014-2020. Retrieved from: https://www.arimr.gov.pl/pomoc-unijna/platnosci-bezposrednie.html.

Bellman, R., Dreyfus, S. 1967. Dynamic programming. Warsaw, PWE.

Bertsekas, D. 2017 Dynamic Programming and Optimal Control, 4th edition. Athena Scientific, Massachusetts.

Charnes, A., Cooper, W. 1961. Management Models and Industrial Applications of Lineal Programming. New York, Wiley.

Cupiała, M., Szeląg-Sikora, A., Niemiec, M. 2015. Optimization of the machinery park with the use of OTR-7 software in context of sustainable agriculture. Agriculture and Agricultural Science Procedia, 7, 64-69.

Galanc, T., Kołwzan W., Pieronek, J. 2016. Informatics systems of decision support and analysis of their security. Operations Research and Decisions, 26(1), 45-53.

Juan, J., Tarjuelo, J.M., Ortega, J.F., Valiente, M., Carrión, P. 1999. Management of water consumption in agriculture: A model for the economic optimization of water use: Application to a sub-humid area. Agricultural Water Management, 40(2-3), 303-313.

Krawiec, B. 1991. Optimization methods in agriculture. Łódź, PWN.

Kopiński, J., Kuś, J. 2011. Influence of organization changes in agriculture on the management of organic matter in soil. Problems of Agricultural Engineering, 19(2), 47-54.

Madlener, R., Glensk, B. 2013 Multi-period portfolio optimization of power generation assets. Operations Research and Decisions, 23(4), 21-38.

Manos, B., Chatzinikolaou, P., Kiomourtzi, F. 2013. Sustainable Optimization of Agricultural Production. APCBEE Procedia, 5, 410-415. https://doi.org/10.1016/j.apcbee.2013.05.071.

Maron, A., Maron, M. 2019. Minimizing the Maximum Risk of Currency Conversion for a Company Buying Abroad. European Research Studies Journal, 22(3), 59-67.

Riesgo, L., Gómez-Limón, J.A. 2006. Multi–criteria Policy Scenario. Analysis for Public Regulation of Irrigated Agriculture. Agricultural Systems, 91(1), 1-28.

Rodríguez, S., Albornoz, V., Plà, L. 2009. A two-stage stochastic programming model for scheduling replacements in sow farms. TOP, 17(1), 171-189.

Sielska, A. 2015. The impact of weights on the quality of agricultural producers' multicriteria decision models. Operations Research and Decisions, 25(4), 51-69.

Smagacz, J. 2000. The role of crop rotation in sustainable agriculture. Diary Pulawski, 120, 411-414.

Spiak, Z., Piszcz U. 2001. Effect of straw fertilization in autumn and spring on some soil properties. Scientific Notebooks of the Agricultural University of Wrocław, 409, 193-215.

Szapiro, T. 2001. Managerial decisions with Excel. Warsaw, PWN.

Taghinezhad, Y. 2019. Optimisation model for a chain logistics problem involving chilled food under conditions of uncertainty. Operations Research and Decisions, 29(2), 103-116.

Zaród, J. 2018. Dynamic decision models for determining the structure of farm production in the region. Academic publishing the West Pomeranian University of Technology, Szczecin.

Zieliński, M., Ziętara, W. 2017. Linear-dynamic programming as a basis for setting the directions of development for field farms against changes in the Common Agricultural Policy in medium-term perspective. Acta Scientiarum Polonorum. Oeconomia, 16(2), 145-153.