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MULTIPLE OBJECTIVE OPTIMIZATION MODELS IN STUDYING THE SUSTAINABLE DEVELOPMENT OF A FARM

WYKORZYSTANIE WIELOKRYTERIALNEGO MODELU OPTYMALIZACYJNEGO DO BADANIA ZRÓWNOWAŻONEGO ROZWOJU GOSPODARSTWA ROLNEGO

Key words: farm income, agricultural production, soil organic matter
Słowa kluczowe: dochód rolniczy, produkcja rolna, materia organiczna w glebie

Abstract. The objective of this paper is to study the sustainable development of agricultural production using the example of an average Polish farm. This study was performed using multiple objective optimization models. Based on statistical data, two models were developed. Model I described a farm involved in plant production, while model II discussed a farm combining plant and animal production. The objective functions for both of these models were related to farm income, agricultural production and the amount of soil organic matter. These objectives aimed at maintaining a balance – vital for sustainable development – between the economic, production and ecological objectives. The results of optimal solutions presented such a production structure that did not cause environmental degradation, provided the highest farm income possible under the given conditions, and ensured high standards of production both for the farmer's own needs and for sale. The agricultural production structures in both the models differ slightly. Farm income gained in the animal farm is approx. 85% higher than that in the farm that only produces crops. In both the models, the application of sustainable production principles helped to achieve a positive soil organic matter balance.

Introduction

The beginnings of the sustainable development concept date back to the seventies of the twentieth century. Later, in 1987 the World Commission on Environment and Development (chaired by Gro Harlem Brundtland) announced its report titled "Our Common Future". It defined sustainable development as one "that meets the needs of the present without compromising the ability of future generations to meet their own needs". Commitments to implement sustainable development were confirmed at the Rio+10 Summit in Johannesburg in 2002, officially known as "the World Summit on Sustainable Development". Today, the principles of sustainable development have been sanctioned by the most important legislative acts and become a requirement in every EU Member State. These principles apply to all sectors of economy, thus including agriculture. Sustainable agriculture is such management that is based on a well-balanced use of natural resources and limitation of the negative impact that agriculture has on the environment. Another aspect of crucial importance for sustainable agriculture is that a balance between production, economic and ecological objectives should be maintained [Staniak 2009]. The production objective is to offer produce, in required amounts, that meets the characteristics expected by the consumer or the processing industry. The economic objective is to generate farm income comparable to wages in other sectors of the national economy. This income should ensure a decent standard of living for the farmers and enable them to modernize and develop their farms. The ecological objective is to ensure a balance in the agrosystem and to prevent environmental degradation. All of the aforementioned objectives will be taken into account in the multiple objective optimization model. Multiple criteria decision models have been taken advantage of in different fields of life. Kunsch et al. [2005] used such models in their research on the automotive industry, and Steuer et Na [2003] in their research on the financial sector. Figueira et al. [2005] edited a publication combining articles on the methods and applications of multiple objective models in many sectors of industry. Many authors have already dealt with agricultural production optimization, including: Manos et al. [2013], Rodriguez et al. [2009]. The purpose of this article is to study the sustainable development of agricultural production using the example of an average Polish farm. As a result of the optimal solution, such a production structure will be determined that does not cause environmental degradation, provides the highest farm income possible under the given conditions, and ensures high standards of production both for the farmer's own needs and for sale.

Material and methods

As material for these studies, Central Statistical Office [Ziółkowska 2013] data on Polish farms in 2013 were used. Some of the data are included in table 1.

Table 1. Main characteristics of an average Polish farm
Tabela 1. Podstawowe charakterystyki przeciętnego gospodarstwa rolnego w Polsce

Specification/*Wyszczególnienie*	Units/*Jedn.*	Values/*Wartości*
Farm area/*Powierzchnia gospodarstw*	ha	11.54
Agricultural land area/*Powierzchnia użytków rolnych*	ha	10.08
Sown area/*Powierzchnia zasiewów*	ha	7.53
Grasslands and pastures area/*Areał łąk i pastwisk*	ha	2.24
Structure of sown, of which/*Struktura zasiewów, w tym:*	%	100
– cereals/*zbóż*	%	73.7
– industrial crops/*roślin przemysłowych*	%	9.1
– potatoes/*ziemniaków*	%	3.4
– feed crops/*roślin pastewnych*	%	10.8
– pulses crops/*roślin strączkowych*	%	0.4
– other crops/*innych upraw*	%	2.6
Yields/*Plony*:		
– cereals/*zbóż*	dt/ha	38.0
– rape/*rzepaku*	dt/ha	29.1
– potatoes/*ziemniaków*	dt/ha	210
– sugar beets/*buraków cukrowych*	dt/ha	580
– grasslands/łąk	dt/ha	50.8
– pastures/*pastwisk*	dt/ha	188
Procurement prices/*Ceny skupu:*		
– cereal grains *ziarn zbóż*	PLN/dt/*zł/dt*	45.76
– potatoes/*ziemniaków*	PLN/dt/*zł/dt*	64.45
– sugar beets/*buraków cukrowych*	PLN/dt/*zł/dt*	14.87
– rape/*rzepaku*	PLN/dt/*zł/dt*	147.34
– beef for slaughter/*żywca wołowego*	PLN/kg/*zł/kg*	6.20
– pork for slaughter/*żywca wieprzowego*	PLN/kg/*zł/kg*	5.39
– milk/*mleka*	PLN/l/*zł/l*	1.36
NPK fertilization/*Nawożenie NPK*	kg/ha	133.0

Source: own study
Źródło: opracowanie własne

Using the data collected, two optimization models were developed, each with three objective functions. The first model was only concerned with plant production, and the second with plant and animal (mixed) production. The overall form of the models was as follows [Kalyanmoy 2001]:

$Ax \leq b$ restrictive (balance) constraints (1)

$x \geq 0$ boundary constraint (2)

$F = max\ \{F_1, F_2, F_3\}$ objective function (3)

where:
A – technical and economic parameter matrix (sown area structure, yields, animal nutrition needs, fertilizer doses, man-hour demand),
b – constant term vector (sown area, area of meadows and pastures, numbers of animals of individual classes and species, employment),
x – decision variables vector (area of arable crops, animals of individual classes and species, sale of produce, purchase of means of production and feed).

The balance constraints are an inequality system that describes the surface and structure of the sown area, crop rotation, actual fertilizer consumption, yields and labour consumption per crop. Crop rotation (sugar beet, potato, oat, wheat, barley, triticale, rape, rye + stubble catch crop and other crops) guarantees good plant coverage of the land and timely performance of agricultural procedures. For sugar beet cultivation, a simplified system was proposed. It consists in sowing the seeds into stubble catch crop in early spring (mulch drilling) and mixing them with the frozen crop residues. This method prevents water and wind erosion, improves soil structure and increases the content of soil organic matter. Potato planting is planned to take place during the ploughing down of the catch crop.

In the animal production model, the restrictive constraints additionally take into account the area of permanent grassland and the changeable composition of the livestock. They balance the yields of crops meant for feeds with the animals' demand for them, and root crop organic fertilization with the manure obtained from the animals. They allow for the sale of surpluses or the purchase of feeds to complement own feed shortages, or for the purchase of high-protein nutritive feeds. In this model, sugar beet was replaced with fodder beet.

The F_1 objective function refers to gross farm income and is expressed using the following formula:

$$F_1 = c^T x \rightarrow max \quad (4)$$

where: c – individual income vector for variables denoting commodity activity or individual outlays incurred by farms involved in non-commodity activity.

The F_2 objective function, maximizing the size of agricultural production, has the following form:

$$F_2 = g^T x \rightarrow max \quad (5)$$

where: g – individual productivity vector for plant and animal production.

The F_3 objective function maximizes the amount of soil organic matter:

$$F_3 = p^T x \rightarrow max \quad (6)$$

where: p – vector of individual soil reproduction or degradation coefficients.

Individual farm income in the first model was calculated as the difference between production value (price ′ yield) and production costs [Augustyńska-Grzymek 2012]. Subsequently, such income was increased by direct subsidies (Single Area Payments and compensatory payments). In the second model, the method for calculating individual income for commodity production variables was not changed. However, for non-commodity activity, individual costs decreased by subsidies were used as objective function parameters.

The costs of variables related to animals only included veterinarian services, animal insurance premiums and electricity consumption. Animal nutrition was secured with own feeds (priced according to production costs) except for industrial mixed feeds (priced according to market prices). Surplus cereal and potato harvest exceeding the farm's own nutrition needs was earmarked for sale.

The yields of individual crops were the coefficients used for the second objective function in the model only concerned with plant production. In the mixed model, different units were used to express plant production (dt/ha) and animal production (kg, l), therefore, it was presented in terms of value in the objective function.

For the purpose of determining the parameters of the third objective function, the soil organic matter reproduction and degradation coefficients according to Eich and Kindler were used (tab. 2).

Table 2**.** Soil organic matter reproduction and degradation coefficients
Table 2. Współczynniki reprodukcji i degradacji materii organicznej gleby

Crops or organic fertilizers/*Rośliny lub nawóz organiczny*	Reproduction (+) and degradation (-) for soils [tons of organic matter per ha]/ *Reprodukcja lub degradacja gleb [t/ha materii organicznej]*			
	soils/*gleby*			
	light/ *lekkie*	medium/ *średnie*	heavy/ *ciężkie*	black soil/ *czarnoziemy*
Root plants/*Okopowe*	- 1.26	-1.40	-1.54	-1.02
Maize/*Kukurydza*	-1.12	-1.15	-1.22	-0.91
Cereals, oilseeds/*Zboża, oleiste*	-0.49	-0.53	-0.56	-0.38
Winter catch crops, cereals for green/ *Poplony ozime, zboża na zielonkę*	-0.32	-0.35	-0.38	-0.25
Pulses/*Strączkowe*	+0.32	+0.35	+0.38	+0.38
Undersown legumes and grass/*Wsiewki motylkowe i trawy*	+0.63	+0.70	+0.77	+0.77
Grass/*Trawy*	+0.95	+1.05	+1.16	+1.16
Legumes/*Motylkowe*	+0.89	+1.96	+2.10	+2.10
Manure/*Obornik**	+0,35		4-5 t fresh weight/*świeżej masy*	
Slurry/*Gnojowica**	+0,28		10-16 t fresh weight/*świeżej masy*	
Straw/*Słoma**	+0,21		about 1.1 t fresh weight/*około 1,1 t świeżej masy*	

* per 1 ton of fertilizer dry matter/*na 1 t materii organicznej*
Source: own study based on [Fotyma, Mercik 2002]
Źródło: opracowanie własne na podstawie [Fotyma, Mercik 2002]

The values of the coefficients provided in the table describe the degree of soil organic matter exhaustion or enrichment expressed in t/ha for the cultivation of a given crop species or the application of a specific dose of organic fertilizers.

There are a few methods for solving multiple objective programming models. The most popular of them is goal programming. It was developed by Charnes and Cooper [Charnes, Cooper 1961]. In this approach, the model constructed needs to be solved separately for each objective (using the linear programming method). After the optimal results are achieved, each objective function is treated as another of the model's restrictive constraints taking the following form:

$$c^T x = dr \quad (7)$$

$$g^T x = pr \quad (8)$$

$$p^T x = so \quad (9)$$

where:

dr – the highest farm income value arrived at in the solution of the single objective model,
pr – the optimal agricultural production value arrived at in the solution in the single objective model,
so – the amount of organic matter preserved in the soil resulting from the optimal solution in the single objective model.

In all of the three additional constraints, a restrictive constraint on the type of equality is present, which needs to be weakened. What we call a full weakening of equality is a transformation in which variables denoting shortage (u^-)or surplus (u^+)occur that reflect the quantities of non-satisfaction of the values arrived at in single-objective models. After the transformation, the given restrictive (flexible) constraints will take the following form:

$$c^T x - u_1^+ + u_1^- = dr \quad (10)$$

$$g^T x - u_2^+ + u_2^- = pr \quad (11)$$

$$p^T x - u_3^+ + u_3^- = so \quad (12)$$

Subsequently, many objectives are replaced with one distance function describing the target value deviation costs (penalties):

$$F = u_1^+ + u_1^- + u_2^+ + u_2^- + u_3^+ + u_3^- \rightarrow min \quad (13)$$

This function features both the variables describing the shortage or surplus of farm income and agricultural production, as no special recommendations exist as to the method of arriving at them. However, the shortage of soil organic matter should be minimized in order to avoid environmental degradation.

Research results

The optimal solutions of multiple objective models showed a production structure the implementation of which will balance the three objectives assumed (tab. 3).

Table 3. Results of the solution of multiple objective models for an average Polish farm
Tabela 3. Wyniki rozwiązań modeli wielokryterialnych przeciętnego gospodarstwa rolnego w Polsce

Specification/*Wyszczególnienie*	Units/*Jedn.*	Models/*Modele*	
		I	II
Sown area/*Powierzchnia zasiewów*	ha	7.53	7.53
Wheat/*Pszenica*	ha	1.15	1.15
Barley/*Jęczmień*	ha	0.61	0.73
Rye/Żyto	ha	1.57	1.69
Oats/*Owies*	ha	0.99	1.06
Triticale/*Pszenżyto*	ha	0.86	0.92
Rape/*Rzepak*	ha	0.96	0.96
Potatoes/*Ziemniaki*	ha	0.41	0.71
Beets/*Buraki*	ha	0.80	0.11
Other crops/*Inne uprawy*	ha	0.18	0.19
Stubble catch crop/*Poplon ścierniskowy*	ha	1.57	-
Grassland/*Łąki*	ha	-	0.92
Pastures/*Pastwiska*	ha	-	1,35
Cows/*Krowy*	heads/*szt.*	-	2
Calves/*Cielęta*	heads/*szt.*	-	2
Young cattle for fattening/*Młode bydło opasowe*	heads/*szt.*	-	2
Sows/*Lochy*	heads/*szt.*	-	1
Piglets/*Prosięta*	heads/*szt.*	-	16
Porkers/*Tuczniki*	heads/*szt.*	-	15
Farm income/*Dochód rolniczy*	PLN/*zł* (EUR)	20 386.90 (4831,02)	31 937.09 (7 568,03)
Agricultural production/*Produkcja rolnicza*		547.80 dt	50 285.68 (11 916,04) PLN/*zł* (EUR)
Organic matter in the soil/*Materia organiczna w glebie*	t	0.39	0.56

Explanation: in parentheses, the value of the euro, 1 EUR = 4,22 PLN/*w nawiasach podano wartość w euro, przyjęty kurs 1 euro = 4,22 zł*
Source: own calculations on MATLAB program
Źródło: obliczenia własne na podstawie programu MATLAB

The table only contains the main results. The remaining information is concerned with the quantities of the produce sold, means of production and mixed feeds purchased, as well as manpower demand. The numbers of cows and sows in the optimal solution in the animal production model reflected their actual numbers. However, the numbers of the remaining animal species were derived from the changeable composition of the livestock.

The values achieved for all the objective functions were the highest that could be achieved by pursuing the three objectives simultaneously.

Summation

For the purposes of these analyses, a traditional farm was chosen that demonstrated no clear production orientation. For this farm, two multiple objective optimization models were developed. Model I was concerned with plant production and model II with plant and animal production. In both of these models, the same crop rotation was considered in which cereal crops amounted to over 70%, root crops to approx. 10%, and rape to not more than 13%. The crop rotation assumed guaranteed good plant coverage of the soil and timely performance of all agricultural procedures. In model II, based on nutritional ingredient balances, an optimization process for the consumption of bulky feeds produced in the farm was performed and the required quantity and type of nutritive feeds that had to be purchased was calculated. The models' optimal solutions showed such a production structure that gave the highest farm income and agricultural production possible under the given conditions and allowed for proper management of the soil's natural resources. Therefore, the models allowed us to study the fulfilment of the economic, production and ecological objectives in an average Polish farm involved in plant production or mixed plant and animal production. The farm income feasible under the sustainable development conditions for a plant-producing form was relatively low and amounted (together with subsidies) to approx. PLN 1698.91 (EUR 402,58) a month (PLN 20386.9 / 12 and EUR 4831,02). It is not comparable to wages in other sectors of the Polish national economy. The average monthly gross remuneration (a measure comparable to farm income) in the business sector according to Central Statistical Office [Zgierska 2013] in 2013 amounted to PLN 2730 (EUR 646,92). The amount of farm income obtained here does not allow the farm to develop.

In farms involved in animal production, farm income was approx. 57% higher than that in farms that only produced crops. It was comparable to net wages in the business sector (PLN 31 937.09 / 12 = 2661.42 and EUR 7568,03/12=2661,42 PLN and 630,57 EUR). In spite of this, many farmers have given up this type of business after Poland joined the EU. The high quality requirements, combined with a lack of funds for modernisation of the farms, have been the main reasons why such farmers have stopped raising livestock.

The value of farm income depends, first of all, on the size and quality of production. By increasing production quality, one can increase exports and domestic sale and, as a result, obtain better prices. Production obtained in the model farm is of high quality. It is so, because the crops were cultivated using low doses of mineral fertilizers and only the indispensable chemical plant protection procedures.

In both the models, applying the principles of sustainable development helped achieve a positive soil organic matter balance (0.39 t and 0.56 t). In the animal producing farm, the manure produced was used to fertilize beets, potatoes and rape using the following doses: 300, 350 and 300 dt/ha, respectively. These doses replenish humus losses throughout the entire crop rotation cycle. In the crops-only farm, organic fertilization took the form of ploughing down the straw and stubble catch crop. However, it needs to be noted that fertilization with straw, even with the application of an additional dose of nitrogen, brings worse production results when compared to the use of manure. Moreover, ploughing down straw too frequently may have negative effects on the emergence and initial growth of some plant species. When straw decomposes in soil, biologically-active compounds are produced that hinder the growth of crops. This phenomenon is prevented by combining fertilization with straw and stubble catch crop cultivation.

The models are suitable for the study sustainable production structure in the Polish farm.

Conclusions

1. Multiple-objective models can be used as a tool supporting research into the sustainable development of farms. They allow for the determination of such a production structure that will guarantee the highest farm income possible under the given conditions, and ensure high standards of production, making sure that environmental degradation is avoided.
2. Farm income obtained as a result of the optimal solution of the multiple objective model for the plant-producing farm is lower than non-agricultural wages and does not allow for farm development.

3. Farm income obtained in the animal-producing farm is comparable to wages in other sectors of the national economy. The high quality standards expected of animal production have reduced animal raising activity, though.
4. The agricultural production structures in both the models differ slightly. Farm income gained in the animal farm is approx. 85% higher than that in the farm that only produces crops.
5. In farms producing crops, there is a possibility of maintaining a positive soil organic matter balance by ploughing down straw and cultivating stubble catch crops, and in farms raising livestock by fertilizing soil with manure.

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Streszczenie

Celem badań było przedstawienie zrównoważonego rozwoju produkcji rolniczej na przykładzie przeciętnego gospodarstwa rolnego w Polsce. Badanie przeprowadzono za pomocą wielokryterialnych modeli optymalizacyjnych. Na podstawie danych statystycznych zbudowano dwa modele. Model I opisywał gospodarstwo rolne z produkcją roślinną, model II z produkcją roślinną i zwierzęcą. Funkcje celu tych modeli dotyczyły dochodu rolniczego, produkcji rolniczej i ilości substancji organicznych w glebie. Kryteria te dążyły do zachowania równowagi, istotnej dla zrównoważonego rozwoju, między celem ekonomicznymi, produkcyjnymi i ekologicznymi. Wyniki rozwiązań optymalnych ustaliły taką strukturę produkcji, która nie degraduje środowiska naturalnego, daje najwyższy, możliwy w danych warunkach dochód rolniczy i zapewnia produkcję o wysokim standardzie, niezbędną na potrzeby własne oraz na sprzedaż. Struktura produkcji roślinnej w rozwiązaniach obu modelach różniła się nieznacznie. Dochód rolniczy uzyskany w gospodarstwie rolnym ze zwierzętami był o około 85% wyższy niż w takim samym gospodarstwie zajmującym się tylko produkcją roślinną. W obu modelach, dzięki stosowanym zasadom zrównoważonej produkcji, uzyskano dodatni bilans substancji organicznych w glebie.

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