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INVESTIGATING MEAT SUBSTITUTE ALTERNATIVES - OPTIMAL SOLUTIONS

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Achieving a complete set of nutritional recommendations for food consumption is currently very challenging. A linear programming diet optimization model appears to be a useful mathematical tool for determining nutrient-based recommendations in nutritionally optimal food combinations. We used linear programming methods to explore optimal patterns of food intake that meet the nutritional recommendations given in the Reference Intakes. The main goal of the paper was to investigate and verify the research assumption that meat can be replaced by legumes. At the same time, we wanted to verify whether the carbon footprint of food will change the optimal structure of food consumption.
We found it very difficult to replace meat with other substitutes than we expected - namely legumes. In the model with price in the basic solution, we arrived at an optimal solution that contained some kind of meat. However, we also reached a similar result by changing the basic solution from prices to emissions represented by the carbon footprint. In the optimal solution, meat was again present, albeit in smaller quantities. Legumes accounted for a tiny amount of grams in consumption.

Keywords: *food items; carbon footprint; emissions; optimal solution; meat, legumes*

INTRODUCTION

Achieving a complete set of nutritional recommendations for food consumption is currently very challenging. A linear programming diet optimization model appears to be a useful mathematical tool for determining nutrient-based recommendations in nutritionally optimal food combinations. We used linear programming methods to explore optimal patterns of food intake that meet the nutritional recommendations given in the Reference Intakes. Current patterns of food consumption, especially meat and dairy products, have a significant impact on the environment. For this reason, we examine food consumption from a sustainability perspective. This modelling study examines the effect of low- or no-meat and no-dairy diets on nutrient intake and assesses nutritional adequacy by comparing these diets to a reference dietary intake. According to FAO (2010), a sustainable diet is defined as "conserving and respecting biodiversity and ecosystems, culturally acceptable, accessible, economically just and affordable, nutritionally adequate, safe and healthy while optimizing natural and human resources". It is estimated that in the European Union, food consumption is responsible for 20-30% of the total environmental impact of total household consumption in the EC (2006). Several studies have assessed the environmental impact of current diets or dietary changes (Perignon, 2016; Payne, 2016), most of which use greenhouse gas emissions (GHGE) as an environmental indicator. These studies almost always find that meat and dairy products are among the biggest contributors to GHGs, while high consumption of vegetables, fruits and pulses/legumes/nuts are associated with the lowest GHGEs (Hyland, 2016; Temme 2015; Vieux, 2012). Temme et al (2015) reported that meat and cheese accounted for approximately 40% of the daily GHG diet in the Netherlands, while potatoes, vegetables and fruit accounted for 9%. These results are consistent with the idea that reducing meat consumption would benefit both health and the environment, as the global increase in meat production exacerbates climate change and increases the risk of some non-communicable diseases, says McMichael (2007). Several studies have investigated the potential of alternative diets to reduce the environmental impact of food consumption by comparing the environmental impact of an observed average diet with hypothetical dietary scenarios (e.g. vegetarian, vegan or flexitarian) (Westhoek, 2014) or scenarios of eating habits considered healthier and more regionally acceptable, such as the Mediterranean and New Nordic diets (van Doore, 2014, Ulaszewska, 2017; Saxe, 2013; Sáez-Almendros, 2013). In most of these studies, scenarios of diets with fewer animal products have less environmental impact than observed diets (van Doore, 2014, Saxe, 2013; Sáez-Almendros, 2013). However, hypothetical dietary scenarios are based on a priori decisions and are not representative of actual food consumption in terms of food choices and energy content, and therefore ignore the factor of cultural acceptability. Moreover, their assessment of diet quality does not consider the entire set of nutritional requirements. The concept of food sustainability means simultaneously combining environmental impact, nutritional adequacy, economic availability and cultural acceptability of food. This type of integrative approach can be implemented using linear programming, which is a unique tool for creating dietary models that consider the multifactorial aspect of dietary sustainability issues by testing the feasibility of complex problems involving several variables and constraints and finding the optimal solution Darmon (2020). A French study based on linear programming found that moderate GHGE reductions (≤30%) are compatible with nutritional adequacy and availability without significant shifts in food groups from the observed diet Perignon (2016). Research in the UK has shown that a healthy diet with reduced GHGEs (-27%) is possible, but for most individuals this would involve significant changes in diet Horgan (2016). In both studies, the emission reduction diets showed optimally lower levels of animal foods, except for fish. However, all of the above studies were country-specific and used heterogeneous modeling or emission assessment methods, making reasonable cross-country comparisons impossible. Applying a harmonized modeling approach to the consumption of more food data in individual European countries would help to derive European policy to improve dietary sustainability.

The main goal of the paper was to investigate and verify the research assumption that meat can be replaced by legumes. At the same time, we wanted to verify whether the carbon footprint of food will change the optimal structure of food consumption.

RESEARCH METHODS

The Materials and Methods should be described with sufficient details to allow others to replicate and build on the published results. Please disclose at the submission stage any restrictions on the availability of materials or information. New methods should be described in detail while well-established methods can be briefly described and appropriately cited.

Materials

Office of Public Health of the Slovak Republic according to § 11 letter o) Act no. 355/2007 Coll. on the protection, support and development of public health and on the amendment and supplementation of certain laws, as amended, declares the updated Recommended nutritional allowances for the population in the Slovak Republic (9th revision) in the attached tables. Recommended nutritional allowances for the population in the Slovak Republic (hereinafter "OVD") create a basic prerequisite for ensuring healthy nutrition (§2 paragraph 1 letter s) of Act no. 355/2007 Coll.) for individual physiological groups of the population and take into account their energy and nutritional requirements according to age, gender, physical load on the body and the physiological state of the body of pregnant and lactating women.

Recommended nutritional allowances for the population (OVD) are determined in the form of scientifically justified bases for establishing requirements for ensuring sufficient sources of nutrition for the population, their quantitative and qualitative aspects, i.e. for the purposes of food production and consumption, setting out the principles of food and nutrition policy, and the development of the main goals and directions in the nutrition of the population, evaluation of the level of food consumption and its nutritional picture, OVD are basic rations designed for practical needs containing 16 tabulated nutritional factors, which are the basis for routine practice and planning to ensure the production and consumption of food by the population. They form supplementary rations for wider scientific research and monitoring purposes (16 nutritional factors), but also for national dietary system and clinical practice. General recommendations in nutrition concern some nutrients whose need and saturation in the population from epidemiological studies is not yet known enough in our country to tabulate them.

In the database, co-emissions of greenhouse gases from 29 different food products. For each product, you can see from which stage of the supply chain its emissions originate. The carbon footprint data comes from the largest meta-analysis of global food systems to date, published in Science by Joseph Poore and Thomas Nemecek (2018). In this study, the authors looked at data from more than 38,000 commercial farms in 119 countries. CO2 is the most important greenhouse gas, but not the only one – agriculture is a large source of greenhouse gases, methane and nitrous oxide. To capture all greenhouse gas emissions from food production, researchers therefore express them in kilograms of "carbon dioxide equivalents". This metric considers not only CO2, but all greenhouse gases.

Average consumer prices of selected products (prices are adjusted for inflation). For this analysis, we use data from the Statistical Office of the Slovak Republic SOSR (2020).

Objective function of linear programming models

Linear programming models are a special class of mathematical programming models. A mathematical programming model is used to describe the characteristics of the optimal solution of an optimization problem by means of mathematical relations. Besides giving a formal description of the problem, the model constitutes the basis for the application of standard optimization algorithms (available as algebraic modelling systems and optimization software) capable of finding an optimal solution, noted Giovanni (2017).

A mathematical programming model consists of the following elements.

- Sets, which group the elements of the system.
- Parameters, the data of the problem, which represent the known quantities depending on the elements of the system.
- Decision (or control) variables: these are the unknown quantities, on which we can act in order to find different possible solutions to the problem.

- Constraints: these are the mathematical relations that describe conditions imposing the feasibility of the solutions. In other words, the constraints distinguish between the combinations of values of the variables representing acceptable solutions and the combinations of values giving non-acceptable solutions.
- Objective function: this is the quantity to maximize or minimize, written as a function of the decision variables.

Solving an optimization problem formulated as a mathematical programming model means deciding the values of the variables that satisfy all the constraints and maximize or minimize the objective function. These values are the solution to the problem.

A Linear Programming model is a mathematical programming model in which:
• the objective function is a linear expression of the decision variables.
• the constraints are given by a system of linear equations and/or inequalities.

The general formulation of tasks for determining the optimal production plan is

$$\min z(x) = \sum_{j=1}^{n} c_j x_j \qquad (1)$$
$$\sum_{j=1}^{n} a_{ij} x_j > b_i, \text{ where all i=1, 2..m}$$
$$x_j > 0, \text{ where all i=1,2…. n}$$

xj – amount of production of the jth product, for j = 1, 2, …, n, cj – valuation of the j-th product (unit profit, product price, etc.), for j = 1, 2, …, n, and ij – the number of units of the i-th production factor consumed for the production of the unit of the j-th product, i = 1, 2, …, m, j = 1, 2, …, n, b i – available quantity of the i-th production factor, i = 1, 2, …, m. In this type of tasks (as well as in all the following ones) it is necessary to determine the vector x* = (x*1 , x*2 , …, x*n) in such a way that the maximum (or minimum) value of the objective function is reached under the specified boundary conditions .

Assumption of linear equations

Objective function (average price per 100 g):

Min z(x) = 0,7027*Beef+ 0,485*Pork+ 0,248*Poultry+ 0,1314* Fish_salmon+ 0,112*Fish_sardine+ 0,15*Fish_tuna+ 0,092*Milk 0,716*Cheese+ 0,155*Eggs+ 0,05*Flour+ 0,153*Bread+ 0,072*Potatoes+ 0,534*Legumes_Bean+ 0,418*Legumes_Lentils+ 0,138*Legume_Peas 0,598*Vegetable_Tomato+ 0,126*Fruit_apple+ 0,169* Fruit_Banana

During the day, people should obtain certain amounts of substances important for their nutrition. When compiling the daily menu, you can choose between two more foods (either meat or legumes) or decide on a combination. The aim of the model is to determine how much food must be purchased for one person for one day in order to achieve the necessary nutritional composition and to keep costs to a minimum. Since the relationships between food and limiting conditions can be assumed to be linear, we can construct a linear programming problem by solving which we determine the minimum cost diet. We will build this task in a similar way as in the previous cases. The quantities of food that must be purchased and which must be non-negative are unknown.

The second model represents sustainability in the context of food consumption. We put the carbon footprint data for each food into the purpose function. The aim of the model is to determine the amount of food that must be purchased for one person for one day in order to achieve the necessary nutritional composition and to keep the carbon footprint to a minimum.

Objective function (CO2 emissions per 100 g):

Min z(x) = 6*Beef+ 0,7*Pork+ 0,6*Poultry+ 0,6* Fish_salmon+ 0,6*Fish_sardine+ 0,6*Fish_tuna+ 0,21*Milk 0,21*Cheese+ 0,45*Eggs+ 0,14*Flour+ 0,14*Bread+ 0,06*Potatoes+ 0,09*Legumes_Bean+ 0,09*Legumes_Lentils+ 0,09*Legume_Peas 0,04*Vegetable_Tomato+ 0,04*Fruit_apple+ 0,04* Fruit_Banana

The Constraints Table 1 is the same for both types of objective function, it contains the same input values.

Table 1. Constraints

Nutrition	Beef	Pork	Poultry	Fish_salmon	Fish_sardine	Fish_Tuna	Milk	Cheese	Eggs	Flour	Bread	Potatoes	Legumes_Bean	Legumes_Lentils	Legumes_Peas	Vegetable_tomato	Fruit_Apple	Fruit_Banana	LHS		RHS
Protein	30,59	30,59	31,40	27,06	24,71	29,41	3,28	12,44	12,00	10,43	8,00	1,48	8,47	9,09	8,16	0,81	0,00	0,85		>=	63
Total fat	12,94	8,24	3,49	10,59	11,76	1,18	3,28	4,44	10,00	0,87	4,00	0,00	0,56	0,51	0,51	0,00	0,00	0,85		>=	85
fatty acid saturated	5,06	2,94	1,05	1,88	1,53	0,35	2,09	2,84	3,20	0,17	0,80	0,00	0,11	0,05	0,05	0,08	0,07	0,17		>=	65
Mono unsaturated	5,65	3,65	1,28	5,29	3,88	0,24	0,98	1,29	3,80	0,09	1,60	0,00	0,06	0,05	0,10	0,08	0,00	0,00		>=	1,7
Poly unsaturated	0,47	0,59	0,81	2,35	5,18	0,35	0,12	0,13	1,40	0,43	0,80	0,07	0,23	0,15	0,15	0,16	0,00	0,08		>=	7
Cholesterol mg	105,88	82,35	84,88	87,06	142,35	57,65	13,52	15,11	426,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00		>=	300
carbohydrate	0,00	0,00	0,00	0,00	0,00	0,00	4,51	2,67	2,00	76,52	48,00	20,00	23,16	20,20	20,92	4,88	15,22	23,73		>=	358
Fiber g	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	2,70	4,40	1,78	8,47	7,88	8,32	1,14	2,68	2,37		>=	26
Calcium	12,94	30,59	15,12	7,06	382,35	21,18	119,26	60,00	50,00	14,78	104,00	8,15	25,99	19,19	13,78	4,88	7,25	5,93		>=	1100
Iron	3,65	0,82	1,05	0,59	2,94	0,94	0,04	0,13	1,40	4,61	3,20	0,30	25056,50	3,33	1,28	0,49	0,14	0,34		>=	17
Potassium	263,53	375,29	255,81	375,29	396,47	569,41	151,64	84,44	122,00	106,96	200,00	328,15	345,20	369,19	362,24	221,95	115,22	395,76		>=	3500
Sodium	70,59	60,00	74,42	65,88	504,71	47,06	49,18	404,89	126,00	1,74	532,00	5,19	1,13	2,02	2,04	8,94	0,00	0,85		>=	2400
Vit A	0,00	2,35	5,81	63,53	67,06	20,00	31,15	48,00	192,00	0,00	0,00	0,00	1,13	1,01	1,02	61,79	5,07	7,63		>=	800
Thiamin B1	0,08	1,15	0,07	0,21	0,08	0,51	0,04	0,02	0,06	0,78	0,40	0,10	0,24	0,17	0,19	0,06	0,01	0,04		>=	1,3
Riboflavin B2	0,28	0,31	0,12	0,18	0,22	0,06	0,16	0,16	0,50	0,50	0,28	0,02	0,06	0,07	0,06	0,05	0,01	0,10		>=	1,5
Niacin	2,71	5,53	13,72	6,71	5,29	11,88	0,08	0,13	0,00	5,91	4,00	1,33	0,51	1,06	0,87	0,65	0,07	0,51		>=	14
ascorbic acid	0,00	0,00	0,00	0,00	0,00	1,18	0,82	0,00	0,00	0,00	0,00	7,41	0,00	1,52	0,51	18,70	5,80	9,32		>=	110

Source: Data gained from WHO and recalculated.

All Variables Must Be Nonnegative. Most linear programming computer packages automatically convert right-hand-side constants into nonnegative values and change constraints into equalities. They assume all variables are nonnegative. If they are not, the problem must be rewritten so that all variables are nonnegative.

RESEARCH RESULTS AND DISCUSSION

Optimal solution – results

Optimal consumption (min-> Price) is following: 74,8 g beef meet, 394,7 g milk, 102,1 g cheese, 53,5 g flour, 153,5 g potatoes, 291,7 g vegetables and 180,8 g fruits. Other food items are not included to the solution. Minimal cost of this optimal solutions presents 2, 73 eur per day. Food expenses are on average 64 euros per person per month in Slovakia. If we were to convert the value of the target value to a month, we would approach 64 euros.

The optimal consumption plan is recommended to consume 0,29 g of beef, 32,8 g pork, 720 g fish tuna, 110 g cheese, 330 g legumes_lentils. Other food items are not included to the solution. Minimal amount of emission which will be produce by these optimal solutions presents 6,21 grams emission per day per person. If we were to multiply the amount of food by the average prices, which turned out to be the optimal solution with the objective function containing the emission values, the cost of food consumption considering the emissions would be 3.59 euros per day.

The Answer Report (Table 2.), which is available whenever a solution has been found, provides basic information about the decision variables and constraints in the model. It also gives you a quick way to determine which constraints are "binding" or satisfied with equality at the solution, and which constraints have slack. The Answer Report records the message that appeared in the Solver Results dialog, the Solving method used to solve the problem, Solver Option settings, and statistics such as the time, iterations and subproblems required to solve the problem.

First shown are the objective function and decision variables, with their original value and final values. Next are the constraints, with their final cell values; a formula representing the constraint; a "status" column showing whether the constraint was binding or non-binding at the solution; and the slack value – the difference between the final value and the lower or upper bound imposed by that constraint. The variable cells and constraints section.

Table 2. Answer report of the Optimal solutions including Price and Optimal solutions including Carbon footprint (CO2 emissions)

	OF: min Price		OF: min CO2	
Nutrition	**RHS Contraints**	**Slack**	**RHS Contraints**	**Slack**
Fiber g	7,87	18,13	26	0,00
Calcium	2638,01	1538,01	1100	0,00
Iron	17,00	0,00	42080,05995	42063,06
Potassium	3500,00	0,00	3500	0,00
Sodium	2400,00	0,00	2400	0,00
Vit A	800,00	0,00	1229,543726	429,54
Thiamin B2	1,47	0,17	1,3	0,00
Riboflavin B3	4,01	2,51	3,892299548	2,39
Niacin	14,00	0,00	14	0,00
ascorbic acid	15,20	94,80	33,33792287	76,66
Protein	107,78	44,78	143,3720079	80,37
Total fat	85,00	0,00	85	0,00
Carbohydrate	163,88	194,12	170,5490198	187,45

Source: own calculations in Solver

If we focus on the Slack variables (OF: min Price) , we can reach the following conclusions. For nutritional items that have a value of Slack = 0, it is clear that the given amount is fully consumed. Overproduction or not binding slack can be seen with Carbohydrate (194.11 units), Proteins (44.78 units), Riboflavin (2.5), Thiamin (0.17), Calcium (1538 units) and Fiber 18.13 units) .

Slack variables (OF: min CO2) show a different structure than in the previous model. We can see that overproduction can be seen in carbohydrates (187.45 units), proteins (80.73 units), ascorbic acid (76.66) riboflavin (2.39), Vit A (429.54) and Iron (42,063, 06 units). For nutritional items that have a value of Slack = 0, it is clear that the given amount is fully consumed.

The Sensitivity Report (see Table 3) is the most useful of the three reports. It is very useful for managerial decisions. The sensitivity report is broken down into two parts.

The primary values of interest in the variable cells section of the sensitivity report are the "Reduced Cost" values for each of the decision variables chosen in the linear programming model. The reduced cost value for each decision variable tells you how much your objective function value will change for a one unit increase in that decision variable.

A reduced cost of -0,07, would indicate that a one unit increase in the final value of the tables decision will result in a decrease of the objective value by 0,07. The objective value in this example is cost and so we will see a increasing costs of 0,07 if we produce one additional unit.

Table 3. Sensitivity report- Shadow prices

	OF: min Price	OF: min CO2
Nutrition	**Shadow Price**	**Shadow Price**
Fiber g	0,00000	-0,05260
Calcium	0,00000	0,00813
Iron	0,00002	0,00000
Potassium	0,00049	0,00145
Sodium	0,00068	0,00479
Vit A	0,00043	0,00000
Thiamin B1	0,00000	1,31638
Riboflavin B2	0,00000	0,00000
Niacin	-0,07020	-0,87834
ascorbic acid	0,00000	0,00000
Protein	0,00000	0,00000
Total fat	-0,00735	-0,08159
Carbohydrate	0,00000	0,00000

Source: own calculations in Solver

If we compare the Shadow price values for the model with prices and the model with emissions, we can conclude that the model with prices does not have significantly high values of shadow prices. We also must start from the context of what we are researching, which is food. Additional nutritional values are unlikely to have an impact on cost minimization. In this regard, the output of the Sensitivity report has no conceptual significance.

We can conclude that diet optimization using linear programming models can effectively translate recommendations based on nutrients into real dietary patterns for the Slovak population, but the output of the research is only in the phase of recommendations, not strict rules.

Levi et al. (2019) investigated a consumer-level model that follows the modeling approach used in Allcott et al. (2019) and Dubois et al. (2014), in which consumers are assumed to purchase quantities of different food groups to maximize their own personal utility, subject to a budget constraint.

Many of the results highlight the importance of the consumer value of nutrition and the need for standardized and accurate methods of measuring it. Currently, surveys often ask about nutrition-related behaviors and nutrition knowledge, notes Levi et al. (2019). However, how the responses actually relate to the actual nutritional value of the consumer is not well understood. Nutritional value plays an important role in determining which portfolio of interventions will be most effective for different consumers. The impact of access on consumer behavior is complex.

A similar analysis to the one we present was performed by Okubo et al. (2015.)To our knowledge, the application of linear programming optimization mathematical models to the development of recommended dietary intake patterns in a real population has not been previously described. Current diets completed a complete set of nutritional recommendations is difficult. A diet optimization model using linear programming is a useful mathematical tool for translating nutrient-based recommendations into realistic nutritional values of an optimal combination of foods including local and culturally specific foods. Okubo et al. (2015) used to investigate optimal food intake patterns that meet the nutritional recommendations of the Dietary Reference Intake (DRI) and at the same time include a selection of typical Japanese foods.

Okubo (2015) found that dietary optimization using linear programming models can effectively translate nutrient-based recommendations into realistic dietary intake patterns for the Japanese population. Further studies are needed to confirm their observations in a Japanese population sample and to investigate the application of linear programming optimization models in other Asian populations.

CONCLUSIONS

The formulations earlier in the supplement give the impression that using linear programming is a clean, simple process. We recognize a problem that fits the linear programming framework, model it, solve it, and then we are done. In practice, using lin- ear programming and other optimization models is not so straightforward, nor is it static. Specifically, our goal in using models is to obtain usable solutions that are better than those we would have obtained without the models, to use the models to revise and update our decisions in a timely fashion, and to increase our confidence in our decisions.

We found it very difficult to replace meat with other substitutes than we expected - namely legumes. In the model with price in the basic solution, we arrived at an optimal solution that contained some kind of meat. However, we also reached a similar result by changing the basic solution from prices to emissions represented by the carbon footprint. In the optimal solution, meat was again present, albeit in smaller quantities. Legumes accounted for a tiny amount of grams in consumption.

It would be beneficial in further research to investigate the optimization in consumption of a specific sample of households and their preferences in consumption. Slovak consumers are known to consume a nutritionally poor and one-sided diet. At the same time, from the point of view of meat consumption, it would be appropriate to investigate which types of meat are nutritionally optimal for consumption. If there was a situation of total exclusion of beef from the offer on the market, what should we replace it with?

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