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A New Multi-objective Optimization Model for Diet Planning of Diabetes Patients under Uncertainty

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Abstract

Aim: The objective of this paper is to design nutrient-adequate, varied and cost-efficient diets for diabetes patients.

Methods: A new multi-objective mixed integer linear programming model under uncertainty is developed to design diet plans for diabetes patients.

Findings: The analysis is conducted on the population of 30 years old men and women in 24.99 and 18.5 body mass index, 1.50, 1.65 and 1.80 (m) height categorized in 4 physical activity levels (sedentary, low, active and very active). The objectives of the model are the minimization of the total amount of saturated fat, sugar and cholesterol and the total cost of the diet plans. The constraints of the model are fulfilling the body's nutrient requirements and the diversity control of each patient's diet. In order to get closer to the real world, fuzzy parameters are considered in the model. To solve the model, a new hybrid solution methodology (Jimenez and epsilon-constraint method) is used to offer the optimal Pareto of non-dominated solutions. Each optimal Pareto of the model consists of diet plans that each patient can choose the proper food based on the taste, availability and cost.

Conclusion: Mathematical modeling of diet planning and study of its optimal solutions can be considered as a decision support tool for the professionals to design the most proper diet plans.

Keywords: Diet planning problem, Multi-objective fuzzy mixed integer linear programming, Jimenez method, Epsilon-constraint method

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Introduction

A large number of people in the world suffer from diabetes, and a significant amount of global health expenditure is spent on this chronic disease. Due to the increasing number of patients afflicted by lifestyle-related diseases, it is necessary to control and design a balanced diet, which is one of the aspects of lifestyle. Healthy diet plan is the most important factor in maintaining and improving the good health of each individual in the whole period of his/her life because not only can it significantly promote the quality of one's life, but also it decreases the development of risk of cancer, cardiovascular disease and diabetes [1]. For many diabetic patients, the most challenging part of the treatment program is to determine what they eat. American diabetes association (ADA) has major emphasis on the role of nutrition therapy and healthy diets on the overall management of diabetes because it can reduce the risk of complications and mortality [2]. Designing a healthy diet for each individual with diabetes, in any stage of disease progression, is extremely important. Hences, the importance of studies on this area is explicit. According to the medical and nutritional science references, essential principles that must be done on the basis of setting up a food plan are as follows [3]:

In the diet of each individual, depending on his/her age, gender and body mass index (BMI) and physical activity level, there is a dietary reference intake of nutrients (such as carbohydrates, fats, proteins, vitamins and minerals, and so forth). It means that the daily intake of each nutrient for each person should be received within an allowed range. No excess or wastage in the use of food groups and planning a diversified balanced diet including all food groups are among the other principle for setting up a diet plan. For decreasing the risk of micro- and macro-complications of the chronic diseases like diabetes, it is necessary to minimize the consumption of sugar, saturated fats and cholesterol. Additionally, there are other parameters that have profound impact on the diet planning problem of the patients. Based on the different ability of patients to pay for their food basket, price is the other important parameter that should be considered to design a cost-efficient diet plan. Table 1 is the review of the literature in this regard.

This table shows that the research techniques such as linear programming, mixed integer programming and fuzzy linear programming have attracted the attention of many researchers to model the diet planning and design the optimal diet plans.

Table 1: Literature review

Researchers	Year	Purpose of the study	Population
Eghbali et al. [3,4]	2011	Determining the optimal diet plan for the type 2 diabetic patients using a mathematical linear programming model	Female 55 years old, low active, BMI 25 kg/m^2 with diabetes
Merwe et al. [5]	2015	Creating an expert system for the purpose of solving multiple facets of the diet problem by creating a rule-based inference engine consisting of goal programming and multi-objective linear programming models	South African individuals
Magdić et al. [6]	2013	Diet optimization for an athlete - recreational bodybuilder for the pretournament period using mathematical models	Athletes
Mamat et al. [7]	2013	Obtaining a complete food plan for human body using fuzzy multi-objective linear programming approach – Creating a Decision Support System for Health to identify chronic and suggest food plan	-
Mamat et al. [8]	2012	Diet planning by using fuzzy linear programming approach	Female, Sedentary, BMI= 24.99 kg/m^2
Lv [1]	2009	Multi-objective mathematic model for nutritional diet optimization and the detailed design process of nutritional diet optimization program based on quantum genetic algorithm (QGA)	Female, 49 years old with hypertension
Maes et al. [9]	2008	Development of an optimization model based on the public health approach for diet optimization	48 adolescents (14–17 years old)
Darmon et al. [10]	2002	Use of linear programming as a method to design nutrient-adequate diets	Malawian children aged 3–6 years
Sklan & Dariel [11]	1993	Diet optimization using mixed integer programming model	-
Anderson & Earl [12]	1983	Use of linear programming to select diets to meet specific nutritional	Thais
Feiferlick [13]	1983	Designing nutritious diets at minimum cost using mathematical models	Severely malnourished in Ethiopia

Therefore, the objective of this study is to develop a new multi-objective mathematical programming model under uncertainty to optimize the food plans for the individuals with diabetes. The contributions of this model are as follows:

- Considering the impact of price parameter of foods in addition to the control of sugar, saturated fat and cholesterol on the food plan
- Considering the diversity of food groups in designing the daily food plans of each patient
- Considering the cost, nutrient ingredients of each food, and required daily intake of food groups as uncertain parameters (fuzzy triangular numbers) in order to close the model to the real world
- Solving the model by a new hybrid solution methodology (Jimenez and epsilon-constraint method) that gives patients the ability to choose the proper diet plan based on the taste, availability of the foods, and the priority of the cost from the non-dominated solutions of the optimal Pareto frontier.

Mathematical model

In this section, a new multi-objective mixed integer programming model under uncertainty is developed in order to optimize the daily diet plan for diabetic patients [3,4, 8]. Decision variables and parameters of the proposed model are defined as follows:

Indices and sets:

$J \in \{1,2,...,n\}$	Selected sample foods for the diet
$I \in \{1,2,...,m\}$	Selected sample nutrients for the diet
$H \in \{1,2,...,h\}$	Food groups (Grain and Starch, Vegetables, Fruits, Poultry and Fish, Dairy products, Fat and oil)
$G_h \subset J$	Set of food group *h*

Parameters:

$\tilde{S}_j$	Amount of sugar macronutrient in 100 g food *j*
$\tilde{F}_j$	Amount of fat macronutrient in 100 g food *j*
$\tilde{C}_j$	Amount of cholesterol macronutrient in 100 g food *j*
$\tilde{P}_j$	Cost (price) of 100 g food *j*
$\tilde{N}_{ij}$	Amount of nutrient (Vitamin, Element, Energy and Macronutrient) i in 100 g food *j*
U_i	The required daily amount of nutrient *i*
L_i	Maximum (tolerable) daily amount of nutrient *i*
$T\tilde{G}_h$	The required daily consumption amount of food group *h*
NG_h	Minimum daily number of different foods from food group *h*
M	Big number

Model Decision Variables:

X_j	100 g food *j* eaten per day
Y_j	$Y_j = 1$ if food *j* existed in the designed diet plan; 0, otherwise.

According to the above notations, a new multi-objective mathematical model for the diet optimization of diabetes patients is presented. The first objective of this model is to minimize the total amount of fat, sugar and cholesterol, while the second one minimizes the total cost (price) of the food plan. With respect to the above assumptions, the multi-objective problem can be developed as follows:

$$Min\ z_1 = \sum_{j=1}^{n} (\tilde{S}_j + \tilde{F}_j + \tilde{C}_j) X_j \qquad (1)$$

$$Min\ z_2 = \sum_{j=1}^{n} \tilde{P}_j X_j \qquad (2)$$

s.t.

$$\sum_{j=1}^{n} \tilde{N}_{ij} X_j \geq L_i \qquad \forall i \qquad (3)$$

$$\sum_{j=1}^{n} \tilde{N}_{ij} X_j \leq U_i \qquad \forall i \qquad (4)$$

$$\sum_{j \in G_h} X_j \geq T\tilde{G}_h \qquad \forall h \qquad (5)$$

$$\sum_{j \in G_h} Y_j \geq NG_h \qquad \forall h \qquad (6)$$

$$X_j \geq 0 \qquad \forall j \qquad (7)$$

$$Y_j = \begin{cases} 1, & if\ X_j > 0 \\ 0, & otherwise \end{cases} \qquad \forall j \qquad (8)$$

Constraints (3) and (4) control the minimum and maximum consumption amounts of nutrients of the daily diet plan, respectively. Constraints (5) and (6) guarantee the diversity of the diet plan. The daily requirement of each food group and the minimum number of the different foods of each food group are controlled by constraints (5) and (6), respectively. Constraint (7) represents the domain of the decision variable X_j. Moreover, constraint (8) shows that when food *j* exists in the diet plan, then decision variable Y_j will be equal to 1.

Transformation of the proposed mathematical model

Due to the complexity of the proposed model based on the definition of the decision variable Y_j, in this section, the previous model will be transformed into an equivalent one by substituting constraints (9) and (10) for constraint (8). Consequently, constraint (8) will be replaced by constraint (11). Constraints (9) and (10) ensure that decision variable Y_j can be equal to 1 only if food *j* exists in the diet plan. Constraint (11) represents the domain of the decision variable Y_j.

$$Y_j \le MX_j \qquad \forall j \qquad (9)$$

$$MY_j \ge X_j \qquad \forall j \qquad (10)$$

$$Y_j \in \{0,1\} \qquad \forall j \qquad (11)$$

Proposed hybrid solution methodology

The considered problem is modeled as a multi-objective fuzzy mixed integer linear programming (MOFMILP) model. To solve this model, we hybridized the two effective approaches (i.e., Jimenez [14] and ε-constraint method [15]). Our proposed method converts the fuzzy programming into an auxiliary crisp model by Jimenez approach and then solves it with ε-constraint multi-objective method.

Multi-objective optimization Model

In the literature, to solve the multi-objective problems, many multi-objective optimization algorithms have been developed based on the following equation [16]:

$$\begin{aligned} & Min\ F(x) = (f_1(x), f_2(x), ..., f_n(x)) \\ & \text{s.t.} \\ & C(x) \le 0 \end{aligned} \qquad (12)$$

Where, $n \ge 2$ is the number of objective functions, $X = (x_1, x_2, ..., x_m)$ is the feasible set of decision vectors, and $C(x)$ shows the model constraints. In multi-objective optimization, one feasible solution that minimizes all objective functions simultaneously does not exist. Therefore, attention is shifted to the Pareto optimal solutions that cannot be improved in any of the objectives without degrading at least one of the other objectives. In mathematical terms, a feasible solution *y* is said to (Pareto) dominate another solution *z*, if [17]:

$$f_i(y) \le f_i(z) \qquad \forall i \in \{1, 2, ..., m\} \qquad (13)$$

$$f_i(y) < f_i(z) \qquad \exists i \in \{1, 2, ..., m\} \qquad (14)$$

Equivalent auxiliary model

Jimenez method [14], which is based on the common ranking, is implemented to convert the proposed multi-objective fuzzy programming model with triangle fuzzy coefficients in the objective functions and the constraints ($\tilde{S}_j, \tilde{F}_j, \tilde{C}_j, \tilde{P}_j, \tilde{N}_{ij}$ and $T\tilde{G}_h$) into an equivalent auxiliary crisp model. Assume $\tilde{c} = (c^p, c^m, c^0)$ is a triangle fuzzy number (Fig. 1), and its membership function is explained as follows:

$$\mu_{\tilde{c}}(x) = \begin{cases} f_c(x) = \dfrac{x - c^p}{c^m - c^p} & \text{if } c^p \le x \le c^m \\ 1 & \text{if } x = c^m \\ g_c(x) = \dfrac{x - c^m}{c^0 - c^m} & \text{if } c^m \le x \le c^0 \\ 0 & \text{if } x \le c^p \text{ or } x \ge c^0 \end{cases} \quad (15)$$

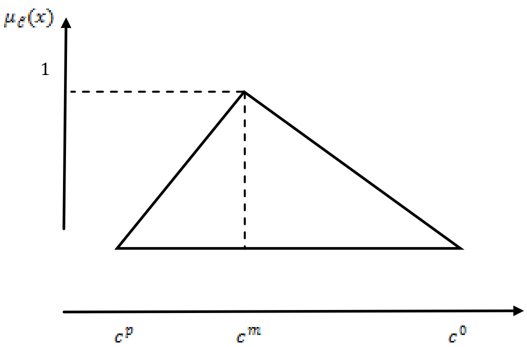

Figure 1: Triangle fuzzy number $\tilde{c}$

Based on this method, expected interval (EI) and expected value (EV) for the triangle fuzzy number $\tilde{c}$ can be calculated as follows:

$$EI(\tilde{c}) = \left[E_1^c, E_2^c\right] = \left[\frac{1}{2}(c^p + c^m), \frac{1}{2}(c^0 + c^m)\right] \quad (16)$$

$$EV(\tilde{c}) = \frac{E_1^c + E_2^c}{2} = \frac{c^p + 2c^m + c^0}{4} \quad (17)$$

Now, a fuzzy mathematical programming model with triangle fuzzy parameters is considered as below:

$$\begin{aligned} &Min\ z = \tilde{c}^t x \\ &\text{s.t.} \\ &\tilde{a}_i x \ge \tilde{b}_i \qquad i = 1, \dots, l \\ &\tilde{a}_i x = \tilde{b}_i \qquad i = l+1, \dots, m \\ &x \ge 0 \end{aligned} \quad (18)$$

By applying the concepts of excepted interval and excepted value for fuzzy numbers, the deterministic (crisp) model can be rewritten as:

$$Min\ EV(\tilde{c})x = \left(\frac{c^p + 2c^m + c^0}{4}\right)x$$

s.t.

$$\begin{aligned} &\left[(1-\alpha)E_2^{a_i} + \alpha E_1^{a_i}\right]x \ge \alpha E_2^{b_i} + (1-\alpha)E_1^{b_i} \qquad i = 1, \dots, l \\ &\left[\left(1-\frac{\alpha}{2}\right)E_2^{a_i} + \frac{\alpha}{2}E_1^{a_i}\right]x \ge \frac{\alpha}{2}E_2^{b_i} + \left(1-\frac{\alpha}{2}\right)E_1^{b_i} \qquad i = l+1, \dots, m \\ &\left[\frac{\alpha}{2}E_2^{a_i} + \left(1-\frac{\alpha}{2}\right)E_1^{a_i}\right]x \le \left(1-\frac{\alpha}{2}\right)E_2^{b_i} + \frac{\alpha}{2}E_1^{b_i} \qquad i = l+1, \dots, m \\ &x \ge 0 \end{aligned} \quad (19)$$

Hence, based on the mentioned descriptions, the model in this paper is converted into an auxiliary crisp model and formulated as follows:

$$Min\ z_1 = \sum_{j=1}^{n} \left(\frac{S_j^o + 2S_j^m + S_j^p}{4} + \frac{F_j^o + 2F_j^m + F_j^p}{4} + \frac{C_j^o + 2C_j^m + C_j^p}{4} \right) X_j \quad (20)$$

$$Min\ z_2 = \sum_{j=1}^{n} \left(\frac{P_j^o + 2P_j^m + P_j^p}{4} \right) X_j \quad (21)$$

s.t.

$$\sum_{j=1}^{n}\left[\left(1-\alpha\right)E_2^{N_{ij}}+\alpha E_1^{N_{ij}}\right]X_j \geq L_i \qquad \forall i \qquad (22)$$

$$\sum_{j=1}^{n}\left[\alpha E_2^{N_{ij}}+\left(1-\alpha\right)E_1^{N_{ij}}\right]X_j \geq U_i \qquad \forall i \qquad (23)$$

$$Y_j \leq MX_j \qquad \forall j \qquad (9)$$

$$MY_j \geq X_j \qquad \forall j \qquad (11)$$

$$\sum_{j\in G_h} X_j \geq \alpha E_2^{TG_h}+\left(1-\alpha\right)E_1^{TG_h} \qquad \forall h \qquad (24)$$

$$\sum_{j\in G_h} Y_j \geq NG_h \qquad \forall h \qquad (6)$$

$$X_j \geq 0 \qquad \forall j \qquad (7)$$

$$Y_j \in \{0,1\} \qquad \forall j \qquad (11)$$

ε–constraint multi-objective solving method

For solving the multi-objective auxiliary crisp model, the ε–constraint method, which depicts an optimal Pareto solution for the decision makers to make the most preferred decisions, is implemented [15]. According to this method, the main steps should be done as follows:

1. Designate one of the objective functions as the main one, and let the others appear as the model constraints.

2. Solve the model with each objective function one by one and compute the optimal and nadir values of each objective function.

3. Compute the range between the optimal and nadir values of each subsidiary objective functions and divide this range into a pre-specified number $\varepsilon_1, \varepsilon_2, ..., \varepsilon_k$.

4. Solve the model with the main objective function and one of the $\varepsilon_1, \varepsilon_2, ..., \varepsilon_k$, iteratively and reporting the Pareto solutions:

$$Min\ f_1(x) \qquad (25)$$

s.t.

$$C(x) \leq 0 \qquad (26)$$

$$f_1(x) \leq \varepsilon_1 \qquad (27)$$

$$f_2(x) \leq \varepsilon_2 \qquad (28)$$

...

$$f_n(x) \leq \varepsilon_n \qquad (29)$$

Experimental results

To show the validity and reliability of the represented model, several numerical experiments were executed by GAMS optimization software (Ver. 23.5) and CPLEX solver on an ASUS Intel(R) Core™ M-5Y71 processor (1.20 GHz) with 8 GB RAM under the windows operating systems, and the computational results have been provided in the following sections.

Data Collection

20 types of sample foods (fish, chicken, soybeans, tangerines, grapefruit, apple, orange, lettuce, lemon, spinach, tomatoes, walnut, olive, oil, low-fat cheese, low-fat milk, low-fat yoghurt, rice, bread, potato and beans) and their food groups (grain and starch, dairy products, fat, vegetables, fruits and meat) as well as 20 types of sample nutrients (Energy, Protein, Carbohydrates, Fiber, Thiamin, Riboflavin, Vit B_{12}, Vit K, Ca, Fe, Mg, Na, Zn, Vit C, Niacin, Vit B_6, Folate, Vit A, Vit E and Vit D) are chosen (Appendix). The set of sample foods

includes super foods for diabetes, as recommended by the American Diabetes Association [18]. References used to extract the parameters of the model are shown in Table 2. Population of this study includes 30 years old men and women with 24.99 and 18.5 BMI, respectively and 1.50, 1.65 and 1.80 (m) height categorized in the four physical activity levels (sedentary, low active, active and very active) [19].

Table 2: References and Table # (Appendix) of the model parameters

Parameter	Reference	Table # (Appendix)
$\tilde{S}_j$	USDA National Nutrient Database [20]	8
$\tilde{F}_j$	USDA National Nutrient Database [20]	
$\tilde{C}_j$	USDA National Nutrient Database [20]	
$\tilde{N}_{ij}$	USDA National Nutrient Database [20]	4-7
U_i	Dietary Reference Intakes (DRIs) [19]	9-12
L_i	Dietary Reference Intakes (DRIs) [19]	
$T\tilde{G}_h$	Law of the Fourth economic, social and cultural development plan of the Islamic Republic of Iran [21] & [3]	3

As shown in Tables 13-16 (Appendix), the experiments are solved for alpha 0.9 and the Pareto solutions including the value of objective functions (total amount of sugar, saturated fat, cholesterol and total cost (price) of each diet plan). The optimal amount of each sample foods in the daily diet plans are considered too. This Pareto-based solution methodology has a significant benefit. Since the non-dominated solutions on the Pareto frontier have no superiority compared to the others, the most proper diet plan (out of the solutions of the Pareto frontier) can be chosen based on the patient's decision. For more explanation, from the three solutions of each Pareto frontier, each patient can choose the best diet plan based on the taste, and availability of the foods, and the priority of the diet plan's cost. The amount of each sample food in the diet plans can be divided into daily meals of each patient. The model is solved by various instances to determine the sensitivity of the solutions. As it is obvious from the results (Figure 2), increasing the patient's BMI and height as well as the consequent increasing need to energy cause an increase in the cost objective function, because the patients needs to consume more foods to respond to their energy requirements. For diabetic patients, it is necessary to consume more complex carbohydrates and fibers and controlled amount of sodium for preventing hypertension and cardiovascular complications;

the computational results show this favorable condition.

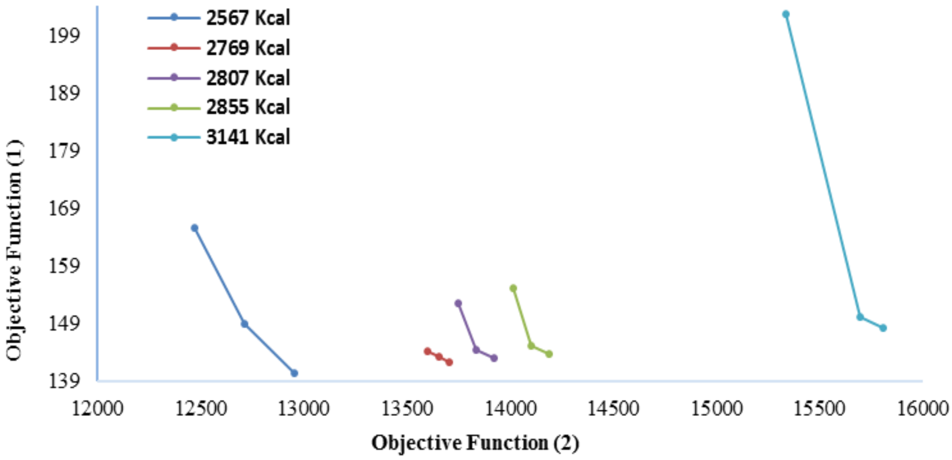

Figure 2: Optimal Pareto fronts for different daily amounts of energy

Conclusion

The importance of the diet therapy in managing diabetes, the profound impact of life-style on delaying the disease complications and mortality rate and also the consequent increase of patients' quality of life clearly demonstrate the urgent need for designing proper diet plan for individuals with diabetes. In this paper, a new multi-objective fuzzy mixed integer linear programming was developed to design a healthy (minimum consumption of sugar, saturated fat and cholesterol), diversified (consisting of all food groups) and cost-efficient diet plan for diabetic patients. To solve the proposed model, we hybridized the two effective approaches (i.e., Jimenez and ε-constraint method); this Pareto-based solution methodology has a significant benefit. Since the non-dominated solutions on the Pareto frontier have no superiority compared to the others, the most proper diet plan (among the solutions of the Pareto frontier) can be chosen based on the patient's decision (the taste and availability of the foods, and the priority of the diet plan's cost). The analysis was conducted on the population of 30 years old men and women with 24.99 and 18.5 BMI, respecting and 1.50, 1.65 and 1.80 (m) height categorized in the four physical activity levels (sedentary, low active, active and very active). The computational results showed the favorability of the designed diet plan for diabetic patients due to consuming more complex carbohydrates and fibers and controlled amount of sodium while the total amount of sugar, saturated fat and cholesterol is minimized.

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Appendix

Table 3: The set of sample foods, food groups and the required daily consumption amount of each food group

Sample food	Beans	Potato	Bread	Rice	Low-fat Yoghurt	Low-fat Milk	Low-fat Cheese	Olive Oil	Walnut	Tomatoes	Spinach	Lemon	Lettuce	Orange	Apple	Grapefruit	Tangerines	Soybeans	Chicken	Fish
Food group	Grain and Starch (G_6)				Dairy products (G_5)			Fat (G_4)		Vegetable (G_3)				Fruit (G_2)				Meat (G_1)		
$T\tilde{G}_h$ (g)	536				225-240			35-40		280				260				98		

Table 4: The value of $E_1^{N_{ij}}$ for each nutrient of series (1) of food ingredients

Sample food	Vit K	Vit B_{12}	Riboflavin	Thiamin	Fiber	Carbohydrate	Protein	Energy
	μg	μg	mg	mg	g	g	g	Kcal
Fish	0.105	0.9	0.05985	0	0	0	17.9	82
Tangerines	0	0	0.036	0.0685	1.94	13.34	0.8325	53
Lemon	0	0	0.021	0.0315	2.8	9.786	0.735	30.45
Beans	5.88	0	0.2226	0.1722	15.96	63.0105	22.491	349.65
Tomatoes	0	0	0.0357	0.0115	1.2	3.9	0.9	18
Grapefruit	0	0	0.021	0	0.105	8.484	0.525	33.6
Lettuce	107.625	0	0.07035	0.0378	1.2	3.2	0.9	14
Walnut	2.835	0	0.1365	0	6.7	13.7	15.2	654
Chicken	0	0.3	0.08925	0.3	0	0	31	165
Low-fat Milk	0	0.4	0.16905	0.1	0	5.2	3.4	42
Potato	1.995	0	0.0336	0	2.2	21.2	2.5	93
Apple	0.63	0	0.0273	0.1	2.4	13.8	0.3	52
Soybeans	0	0	0.16275	0.30375	6	9.9	16.6	173
Olive Oil	63.21	0	0	0	0	0	0	884
Low-fat Cheese	0	1.7	0.17325	0	0	3.4	28.4	179
Spinach	507.045	0	0.1848	0.1	2.2	3.6	2.9	23
Rice	0	0	0.01365	0	1	21.1	2	97
Orange	0	0	0.042	0.1	2.4	11.7	0.9	47
Bread	4.9	0	0.253	0.5	2.4	50.6	7.6	266
Low-fat Yoghurt	0	0.6	0.278	0	0	7	5.2	63

Table 5: The value of $E_2^{N_{ij}}$ for each nutrient of series (1) of food ingredients

Sample food	Vit K	Vit B_{12}	Riboflavin	Thiamin	Fiber	Carbohydrate	Protein	Energy
	µg	µg	mg	mg	g	G	G	Kcal
Fish	0.115	0.9	0.06555	0	0	0	17.9	82
Tangerines	0	0	0.036	0.0895	1.8	13.34	0.8775	53
Lemon	0	0	0.023	0.0345	3.22	10.718	0.805	33.35
Beans	6.44	0	0.2438	0.1886	17.48	69.0115	24.633	382.95
Tomatoes	0	0	0.0391	0	1.2	3.9	0.9	18
Grapefruit	0	0	0.023	0.0414	0.115	9.292	0.575	36.8
Lettuce	117.875	0	0.07705	0	1.2	3.2	0.9	14
Walnut	3.105	0	0.1495	0.3	6.7	13.7	15.2	654
Chicken	0	0.3	0.09775	0.1	0	0	31	165
Low-fat Milk	0	0.4	0.18515	0	0	5.2	3.4	42
Potato	2.185	0	0.0368	0.1	2.2	21.2	2.5	93
Apple	0.69	0	0.0299	0	2.4	13.8	0.3	52
Soybeans	0	0	0.17825	0.2	6	9.9	16.6	173
Olive Oil	69.23	0	0	0	0	0	0	884
Low-fat Cheese	0	1.7	0.18975	0	0	3.4	28.4	179
Spinach	555.335	0	0.2024	0.1	2.2	3.6	2.9	23
Rice	0	0	0.01495	0	1	21.1	2	97
Orange	0	0	0.046	0.1	2.4	11.7	0.9	47
Bread	4.9	0	0.253	0.5	2.4	50.6	7.6	266
Low-fat Yoghurt	0	0.6	0.278	0	0	7	5.2	63

Table 6: The value of $E_1^{N_{ij}}$ for each nutrient of series (2) of food ingredients

Sample food	Vit D	Vit E	Vit A	Folate	Vit B6	Niacin	Vit C	Zn	Na	Mg	Fe	Ca
	µg	mg	µg	µg	mg	Mg	mg	mg	mg	mg	mg	mg
Fish	18.9	0.6	13.5	7	0.1701	1.701	2.9	0.336	71	29	0.3	7
Tangerines	0	0.2	34	16	0.078	0.376	26.7	0.07	2	12	0.1625	37
Lemon	0	0.1575	1.25	8.4	0.04515	0.105	30.555	0.063	2.1	6.3	0.63	27.3
Beans	0	0	0	0	0.41685	0.4494	0.81375	2.394	5.25	144.9	5.3235	87.15
Tomatoes	0	0.5	75	15	0.0588	0.62265	9.45	0.147	5	11	0.3	10
Grapefruit	0	0.1365	49	10.5	0.0441	0.21	32.76	0.0525	0	8.4	0.063	9.45
Lettuce	0	0.1365	386.5	39.9	0.0777	0.32865	4.2	0.189	10	7	0.4	18
Walnut	0	0.7	1.25	98	0.56385	0.4935	1.3	3.2445	2	158	2.9	98
Chicken	1.05	0.7	11.25	4	0.5565	7.96215	0	0.6615	74	29	1	15
Low-fat Milk	0	0	33	5	0.0441	0.0882	0	0.399	4	11	0	119
Potato	0	0	0	28	0.30975	1.1067	9.6	0.3045	1	28	1.1	15
Apple	0	0.2	2.25	3	0.03885	0.09555	4.6	0.042	1	5	0.1	6
Soybeans	0	0.4	8.25	54	0.063	1.3125	1.7	0.9555	1	86	5.1	102
Olive Oil	0	14.3	0	0	0	0	0	0	0	0	0.6	1
Low-fat Cheese	0	0.1	24	6	0.05985	0.10815	0	0.399	260	36	0.2	961
Spinach	0	2	502.5	194	0.1428	0.46095	28.1	0.5145	79	79	2.7	99
Rice	0	0	0	1	0.0273	0.3045	0	0.4305	5	5	0.1	2
Orange	0	0.2	11.5	30	0.063	0.2961	53.2	0.0735	0	10	0.1	40
Bread	0	0.2	0	111	0.111	5.62	0	1.19	681	23	3.7	151
Low-fat Yoghurt	0	0	1	11	0.063	0.208	0.8	0.52	70	17	0.1	183

Table 7: The value of $E_2^{N_{ij}}$ for each nutrient of series (2) of food ingredients

Sample food	Vit D	Vit E	Vit A	Folate	Vit B6	Niacin	Vit C	Zn	Na	Mg	Fe	Ca
	µg	mg	µg	µg	mg	Mg	mg	mg	mg	mg	mg	mg
Fish	20.7	0.6	40.5	7	0.1863	1.863	2.9	0.368	71	29	0.3	7
Tangerines	0	0.2	34	16	0.078	0.376	26.7	0.07	2	12	0.1875	37
Lemon	0	0.1725	1.75	9.2	0.04945	0.115	33.465	0.069	2.3	6.9	0.69	29.9
Beans	0	0	0	0	0.45655	0.4922	0.89125	2.622	5.75	158.7	5.8305	95.45
Tomatoes	0	0.5	75	15	0.0644	0.68195	10.35	0.161	5	11	0.3	10
Grapefruit	0	0.1495	55	11.5	0.0483	0.23	35.88	0.0575	0	9.2	0.069	10.35
Lettuce	0	0.2	419.5	29	0.0851	0.35995	4.6	0.207	10	7	0.4	18
Walnut	0	0.7	1.75	98	0.61755	0.5405	1.3	3.5535	2	158	2.9	98
Chicken	1.15	0.3	19.75	4	0.6095	8.72045	0	0.7245	74	29	1	15
Low-fat Milk	0	0	33	5	0.0483	0.0966	0	0.437	4	11	0	119
Potato	0	0	0	28	0.33925	1.2121	9.6	0.3335	1	28	1.1	15
Apple	0	0.2	2.75	3	0.04255	0.10465	4.6	0.046	1	5	0.1	6
Soybeans	0	0.4	8.75	54	0.069	1.4375	1.7	1.0465	1	86	5.1	102
Olive Oil	0	14.3	0	0	0	0	0	0	0	0	0.6	1
Low-fat Cheese	0	0.1	50	6	0.06555	0.11845	0	0.437	260	36	0.2	961
Spinach	0	2	569.5	194	0.1564	0.50485	28.1	0.5635	79	79	2.7	99
Rice	0	0	0	1	0.0299	0.3335	0	0.4715	5	5	0.1	2
Orange	0	0.2	12.5	30	0.069	0.3243	53.2	0.0805	0	10	0.1	40
Bread	0	0.2	0	111	0.111	5.62	0	1.19	681	23	3.7	151
Low-fat Yoghurt	0	0	1	11	0.063	0.208	0.8	0.52	70	17	0.1	183

Table 8: The value of $EV(\tilde{c})$ coefficients of the objective function (1)

Sample food	Sugar (g)	Saturated fat (g)	Cholesterol (mg)
Low-fat Yoghurt	7	0	5
Bread	4.3	0.7	0
Orange	9.4	0	0
Rice	0.1	0	0
Spinach	0.4	0.1	0
Low-fat Cheese	1.3	3.3	8
Olive Oil	0	13.7	0
Soybeans	3	1.3	0
Apple	10	0	0
Potato	1.2	0	0
Low-fat Milk	5.2	0	0
Chicken	0	1	68.5
Walnut	2.6	6.1	0
Lettuce	2	0	0
Grapefruit	7.1	0	0
Tomatoes	2.6	0	0
Beans	2.99	0.1775	0
Lemon	2.1	0	0
Tangerines	10.5	0	0
Fish	0	1	57

Table 9: Required daily amount of nutrients series (1)

Gender	Age Range	Vit K	Vit B_{12}	Riboflavin	Thiamin	Fiber	Carbohydrate	Protein
		µg	µg	mg	mg	g	g	g
Men	[9,13]	60	1.8	0.9	0.9	31	130	34
	[14,18]	75	2.4	1.3	1.2	38	130	52
	[19,30]	120	2.4	1.3	1.2	38	130	56
	[31,50]	120	2.4	1.3	1.2	38	130	56
	[51,70]	120	2.4	1.3	1.2	30	130	56
	70>	120	2.4	1.3	1.2	30	130	56
Women	[9,13]	60	1.8	0.9	0.9	31	130	34
	[14,18]	75	2.4	1	1	38	130	52
	[19,30]	90	2.4	1.1	1.1	38	130	56
	[31,50]	90	2.4	1.1	1.1	38	130	56
	[51,70]	90	2.4	1.1	1.1	30	130	56
	70>	90	2.4	1.1	1.1	30	130	56

Table 10: Required daily amount of nutrients series (2)

Gender	Age Range	Vit D	Vit E	Vit A	Folate	Vit B6	Niacin	Vit C	Zn	Na	Mg	Fe	Ca
		µg	mg	µg	µg	Mg	mg	mg	mg	mg	mg	mg	mg
Men	[9,13]	5	11	600	300	1	12	45	8	1500	240	8	1300
	[14,18]	5	15	900	400	1.3	16	75	11	1500	410	11	1300
	[19,30]	5	15	900	400	1.3	16	90	11	1500	400	8	1000
	[31,50]	5	15	900	400	1.3	16	90	11	1500	420	8	1000
	[51,70]	10	15	900	400	1.3	16	90	11	1300	420	8	1200
	70>	15	15	900	400	1.3	16	90	11	1200	420	8	1200
Women	[9,13]	5	11	600	300	1	12	45	8	1500	240	8	1300
	[14,18]	5	15	700	400	1.2	14	65	9	1500	360	15	1300
	[19,30]	5	15	700	400	1.3	14	75	8	1500	310	18	1000
	[31,50]	5	15	700	400	1.3	14	75	8	1500	320	18	1000
	[51,70]	10	15	700	400	1.5	14	75	8	1300	320	8	1200
	70>	15	15	15	15	700	400	1.5	14	75	8	1200	320

Table 11: Tolerable daily amount of nutrients series (2)

Gender	Age Range	Vit D	Vit E	Vit A	Folate	Vit B6	Niacin	Vit C	Zn	Na	Mg	Fe	Ca
		µg	mg	µg	µg	mg	mg	mg	mg	mg	mg	mg	mg
Men	[9,13]	50	600	1700	600	60	20	1200	23	2200	350	40	2500
	[14,18]	50	800	2800	800	80	30	1800	34	2300	350	45	2500
	[19,30]	50	1000	3000	1000	100	35	2000	40	2300	350	45	2500
	[31,50]	50	1000	3000	1000	100	35	2000	40	2300	350	45	2500
	[51,70]	50	1000	3000	1000	100	35	2000	40	2300	350	45	2500
	70>	50	1000	3000	1000	100	35	2000	40	2300	350	45	2500
Women	[9,13]	50	600	1700	600	60	20	1200	23	2200	350	40	2500
	[14,18]	50	800	2800	800	80	30	1800	34	2300	350	45	2500
	[19,30]	50	1000	3000	1000	100	35	2000	40	2300	350	45	2500
	[31,50]	50	1000	3000	1000	100	35	2000	40	2300	350	45	2500
	[51,70]	50	1000	3000	1000	100	35	2000	40	2300	350	45	2500
	70>	50	1000	3000	1000	100	35	2000	40	2300	350	45	2500

Table 12: Required daily amount of energy for 30 years old men and women

Height (m)	Physical Activity Level (PAL)	Energy requirements for Women		Energy requirements for Men	
		BMI-kg/m² 24.99	BMI-kg/m² 18.5	BMI-kg/m² 24.99	BMI-kg/m² 18.5
1.50	Sedentary	1762	1625	2080	1848
	Low active	1956	1803	2267	2009
	Active	2198	2025	2506	2215
	High active	2489	2291	2898	2554
1.65	Sedentary	1982	1816	2349	2068
	Low active	2202	2016	2566	2254
	Active	2477	2267	2842	2490
	High active	2807	2567	3296	2880
1.80	Sedentary	2211	2015	2635	2301
	Low active	2459	2239	2884	2513
	Active	2769	2519	3200	2782
	High active	3141	2855	3720	3225

Table 13: Computational results: The Pareto optimal solutions for 30 years old man with diabetes

BMI-kg/m²	Height (m)	Physical Activity Level (PAL)	Pareto solution (1)		Pareto solution (2)		Pareto solution (3)	
			Z_1	Z_2	Z_1	Z_2	Z_1	Z_2
18.5	1.50 & 1.65	Sedentary	225.865	13703.217	225.149	13975.121	224.506	14247.025
		Low active	225.865	13703.217	225.149	13975.121	224.506	14247.025
		Active	225.865	13703.217	225.149	13975.121	224.506	14247.025
		High active	225.865	13703.217	225.149	13975.121	224.506	14247.025
	1.80	Sedentary	225.865	13703.217	225.149	13975.121	224.506	14247.025
		Low active	225.865	13703.217	225.149	13975.121	224.506	14247.025
		Active	225.865	13703.217	225.149	13975.121	224.506	14247.025
		High active	225.865	13703.217	225.149	13975.121	224.506	14247.025
24.99	1.50	Sedentary	225.865	13703.217	225.149	13975.121	224.506	14247.025
		Low active	225.865	13703.217	225.149	13975.121	224.506	14247.025
		Active	225.865	13703.217	225.149	13975.121	224.506	14247.025
		High active	225.865	13703.217	225.149	13975.121	224.506	14247.025
	1.65	Sedentary	225.865	13703.217	225.149	13975.121	224.506	14247.025
		Low active	225.865	13703.217	225.149	13975.121	224.506	14247.025
		Active	225.865	13703.217	225.149	13975.121	224.506	14247.025
		High active	313.691	16580.592	310.269	16650.650	306.846	16720.707
	1.80	Sedentary	225.865	13703.217	225.149	13975.121	224.506	14247.025
		Low active	225.865	13703.217	225.149	13975.121	224.506	14247.025
		Active	252.144	15332.812	238.535	15822.212	231.508	16311.613
		High active	230.999	18241.840	220.512	19109.365	213.920	19976.891

Table 14: Computational results: The Pareto optimal solutions for 30 years old woman with diabetes

BMI-kg/m^2	Height (m)	Physical Activity Level (PAL)	Pareto solution (1)		Pareto solution (2)		Pareto solution (3)	
			Z_1	Z_2	Z_1	Z_2	Z_1	Z_2
18.5	150 & 1.65	Sedentary	140.281	12954.94	148.836	12712.47	165.559	12470
		Low active	140.281	12954.94	148.836	12712.47	165.559	12470
		Active	140.281	12954.94	148.836	12712.47	165.559	12470
		High active	140.281	12954.94	148.836	12712.47	165.559	12470
	1.80	Sedentary	140.281	12954.94	148.836	12712.47	165.559	12470
		Low active	140.281	12954.94	148.836	12712.47	165.559	12470
		Active	140.281	12954.94	148.836	12712.47	165.559	12470
		High active	143.673	14193.18	145.24	14104.84	155.224	14016.5
24.99	1.50	Sedentary	140.281	12954.94	148.836	12712.47	165.559	12470
		Low active	140.281	12954.94	148.836	12712.47	165.559	12470
		Active	140.281	12954.94	148.836	12712.47	165.559	12470
		High active	140.281	12954.94	148.836	12712.47	165.559	12470
	1.65	Sedentary	140.281	12954.94	148.836	12712.47	165.559	12470
		Low active	140.281	12954.94	148.836	12712.47	165.559	12470
		Active	140.281	12954.94	148.836	12712.47	165.559	12470
		High active	142.93	13921.68	144.461	13835.34	152.423	13749
	1.80	Sedentary	140.281	12954.94	148.836	12712.47	165.559	12470
		Low active	140.281	12954.94	148.836	12712.47	165.559	12470
		Active	142.341	13706.75	143.258	13655	144.234	13600
		High active	148.106	15810.82	150.089	15699	202.741	15336.66

Table 15: Computational results: The optimal daily diet plan for 30 years old men with diabetes and BMI-18.5 kg/m^2

Height (m)	Physical Activity Level (PAL)	Pareto frontier #	Optimal daily diet plan for diabetes patients																			
			Fish	**Tangerines**	**Lemon**	**Beans**	**Tomatoes**	**Grapefruit**	**Lettuce**	**Walnut**	**Chicken**	**Low-fat Milk**	**Potato**	**Apple**	**Soybeans**	**Olive Oil**	**Low-fat Cheese**	**Spinach**	**Rice**	**Orange**	**Bread**	**Low-fat Yoghurt**
1.50	Sedentary Low active Active High active	1	22		159.3	62.5	10	10	300	15.3	76	289.6		232.3		86.8			300	17.7	300	300
		2	22		160	53.7	10	10	300	20.6	76	290.7		123.4		86.5			300	126.6	300	300
		3	22	-	160	44.7	10	10	300	25.9	76	292.5		10		86.3			300	240	300	300
1.65	Sedentary Low active Active High active	1	22		159.3	62.5	10	10	300	15.3	76	289.6		232.3		86.8			300	17.7	300	300
		2	22		160	53.7	10	10	300	20.6	76	290.7		123.4		86.5			300	126.6	300	300
		3	22	-	160	44.7	10	10	300	25.9	76	292.5		10		86.3			300	240	300	300
1.80	Sedentary Low active Active	1	22		159.3	62.5	10	10	300	15.3	76	289.6		232.3		86.8			300	17.7	300	300
		2	22		160	53.7	10	10	300	20.6	76	290.7		123.4		86.5			300	126.6	300	300
		3	22	-	160	44.7	10	10	300	25.9	76	292.5		10		86.3			300	240	300	300
	High active	1	22	35.2	45.3	15.9	10		300	46.3	76	271.7		300		91			300	300	300	300
		2	22	10	104	13.5	10		300	54.5	76	232.3		300		91			300	250.4	300	300
		3	22		160	10	10	10	300	60.7	76	194.3		279.3		91			300	214.8	300	300

Table 16: Computational results: The optimal daily diet plan for 30 years old women with diabetes and BMI-24.99 kg/m^2

Height (m)	Physical Activity Level (PAL)	Pareto frontier #	Fish	Tangerines	Lemon	Beans	Tomatoes	Grapefruit	Lettuce	Walnut	Chicken	Low-fat Milk	Potato	Apple	Soybeans	Olive Oil	Low-fat Cheese	Spinach	Rice	Orange	Bread	Low-fat Yoghurt
1.50	Sedentary Low active Active High active	1	26.2	30.4	90.5	0	125.7	0	300	10	0	0	10	300	71.8	79.2	97.6	0	300	300	297.3	84.2
		2	40.7	10	90.5	0	252.3	0	300	10	0	0	10	300	57.3	75	84.5	0	270.9	300	298.6	99.7
		3	56.4	46.1	90.5	0	300	0	300	0	300	10	0	0	17.6	300	41.6	72.8	218.4	300	300	159
1.65	Sedentary Low active Active	1	26.2	30.4	90.5	0	125.7	0	300	10	0	0	10	300	71.8	79.2	97.6	0	300	300	297.3	84.2
		2	40.7	10	90.5	0	252.3	0	300	10	0	0	10	300	57.3	75	84.5	0	270.9	300	298.6	99.7
		3	56.4	46.1	90.5	0	300	0	300	0	300	10	0	0	17.6	300	41.6	72.8	218.4	300	300	159
	High active	1	26.2	30.4	90.5	0	125.7	0	300	10	0	0	10	300	71.8	98.6	97.6	0	300	300	297.3	84.2
		2	26.2	55.8	90.5	0	58.7	0	300	10	0	0	23.6	300	71.8	96.8	94.6	0	300	300	298	92.6
		3	26.2	140	63.9	0	10	0	300	10	0	0	10	300	71.8	94.9	88.7	0	300	300	298.7	109.3
1.80	Sedentary Low active	1	26.2	30.4	90.5	0	125.7	0	300	10	0	0	10	300	71.8	79.2	97.6	0	300	300	297.3	84.2
		2	40.7	10	90.5	0	252.3	0	300	10	0	0	10	300	57.3	75	84.5	0	270.9	300	298.6	99.7
		3	56.4	46.1	90.5	0	300	0	300	0	300	10	0	0	17.6	300	41.6	72.8	218.4	300	300	159
	Active	1	26.2	30.4	90.5	0	125.7	0	300	10	0	0	10	300	71.8	94.3	97.6	0	300	300	297.3	84.2
		2	26.2	45.6	90.5	0	85.5	0	300	10	0	0	18.1	300	71.8	93.2	95.8	0	300	300	297.7	89.2
		3	26.2	61.8	90.5	0	42.9	0	300	10	0	0	26.8	300	71.8	92.1	93.9	0	300	300	298.2	94.6
	High active	1	26.2	30.4	90.5	0	125.7	0	300	10	0	0	10	300	71.8	136.4	97.6	0	300	300	297.3	84.2
		2	66.1	96.9	90.5	0	10	0	300	10	31.9	0	207.9	300	0	123	976.6	0	300	300	299.9	67.9
		3	40.2	121	90.5	0	10	0	300	10	57.8	69.9	191.8	300	0	120.1	93.2	0	288.5	300	300	0