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A Mathematical Model of Diet Menu Problem Based on Boolean Linear Programming Approach

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Abstract. This study aims to model the diet menu problem based on a Boolean Linear Programming approach. A balanced diet is the key to a healthy lifestyle. A balanced diet is a diet that combines foodstuffs in the right amount of food components in one menu (dishes using certain recipes). When you have an unbalanced diet, your body will not get the right amount of nutrients. This is what causes the importance of managing the diet menu. Because of that, a diet menu problem model was formed based on the Boolean Linear Programming approach to cover a varied range of daily diet menu management and meet daily nutritional needs while minimizing costs. The stages of establishing the diet menu problem model are carried out by determining the notations, parameters, variables, objective functions, and some constraints related to the diet menu.

Keywords : Mathematical model, Diet menu problem, Linear programming approach

INTRODUCTION

One of the current modern public health problems that cause economic pressure is the increase in chronic diseases and obesity. Unhealthy lifestyles and the emergence of modern foods and drinks that are high in sodium, sugar, or excessive carbohydrates exacerbate this situation, so it is necessary to pay attention to the amount of food components that enter the body. A balanced diet is the key to a healthy lifestyle. A balanced diet combines foodstuffs in the right amount of food components such as energy, fiber, protein, fat, vitamins, and minerals, thereby providing benefits to the body, for example, providing energy, reducing the risk of health problems and making a person feel better. When you have an unbalanced diet, your body will not get the right amount of nutrients. This is what causes the importance of managing a diet menu that meets the number of foodstuffs, daily food components, and a varied menu (Hui & Sufahani, 2019).

A person's food intake depends on the foodstuffs and the food components contained in these foods. Different foodstuffs certainly have different constituent components. Foodstuffs contain components such as carbohydrates, proteins, fats, vitamins, and other food components in known proportions. Knowing the minimum and maximum quantities of each food component that a person needs, as well as the supply and cost of that diet, we can develop plans to meet nutritional needs at the lowest cost and how to model diet menu problem (Pichugina, 2020). The problem of diet menus has been widely discussed in previous studies, especially when implementing linear programming. This problem is modeled and solved in different ways depending on the application (Gautam & Gulhane, 2023; Gumustekin et al., 2014; Hsiao & Chang, 2010; Pichugina, 2020; Sierksma, 2001; Stigler, 1945).

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In general, when preparing a diet menu in a small area, such as a family, of course, a housewife will not find it difficult to determine a diet menu with foodstuffs and food components contained therein, as well as preparing various recipes that are used to process them into a menu. so that constraints regarding food components such as nutrition, vitamins, minerals, and others can be fulfilled. However, if food production is considered in a larger scope, solving the problem of compiling a diet menu that meets daily foodstuffs and food components with special requirements is a complicated matter, because it requires, for example, menus with certain recipes, menus with prohibited recipes, menus with certain food components, the menu must be varied, the amount of food consumed, and so on. It aims to have a positive impact on the health of people who run certain diet programs.

In linear programming applications, especially integer programming, the diet menu problem already covers a large scope, but it still needs some additions to the decision variables by applying the Boolean Linear Programming formulation, so that it covers large and varied dimensions. For example, in the application of the Boolean Linear Programming formulation, a daily diet menu with 4 consumption times, five types of dishes, and 50 recipes for each type of dish will produce 1000 dimensions. This means that recipes may not be applied more than once throughout the day and the menu becomes more varied. Conversely, if you only apply integer linear programming, there will be 250 dimensions where it states that a recipe may be used more than once throughout the day so that the menu can be repeated (Pichugina, 2020).

Based on this explanation, the authors conducted research to form a diet menu problem model by applying the Boolean Linear Programming formulation which was formulated in the form of an integer linear programming, modified and expanded to cover a range of daily diet menu management that varies and meets the needs daily nutrition while minimizing costs.

PRELIMINARIES

Diet Menu Problem

The Diet Menu Problem is a well-known optimization problem that has been studied extensively in the field of operations research. The problem involves designing a daily menu that meets the nutritional requirements of a group of individuals while minimizing the cost of the food items. There has been a growing interest in this problem in recent years due to the increasing prevalence of diet-related health issues such as obesity, diabetes, and heart disease. The Diet Menu Problem has been studied extensively in the literature, with various approaches proposed to solve the problem. One of the earliest approaches was the Linear Programming (LP) approach, which involves formulating the problem as a linear program and solving it using LP techniques. This approach was first proposed by Stigler in 1945 and has since been used by many researchers (Stigler, 1945). Another approach that has been used to solve the Diet Menu Problem is the Integer Programming (IP) approach. This approach involves formulating the problem as an IP problem and solving it using IP techniques. The IP approach is more effective than the LP approach in solving the problem, especially when dealing with discrete variables (Sabino et al., 2015; Sierksma, 2001). In recent years, there has been a growing interest in using metaheuristic algorithms to solve the Diet Menu Problem. Metaheuristic algorithms are optimization algorithms that are inspired by natural phenomena such as evolution, swarm behavior, and annealing. These algorithms have been shown to be effective in solving complex optimization problems, including the Diet Menu Problem (Gautam & Gulhane, 2023). Sometimes, the diet menu problems are considered to be optimized in multi-objective formulations (Eghbali et al., 2012; Kaldirim & Kose, 2006; Khan et al., 2021; Nasution, 2020).

Boolean Linear Programming

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The problem (PMP) is a distance-based optimization problem. The problem places p facilities, maps the demand points such that each demand point maps to one facility, and finds the sum of the weighted distances between all demand points and their associated facilities. minimized. The basic PMP model, which has remained virtually unchanged for the last 30 years, is ReVelle and Swain's integer programming formulation. This formulation contains Boolean-valued decision variables, so it is called the Boolean Linear Programming formulation (Pardalos et al., 2013).

In recent years, Boolean Linear Programming (BLP) has emerged as a powerful tool for solving optimization problems in various fields, including computer science, engineering, and economics. BLP is a mathematical programming technique that involves the use of Boolean variables and linear constraints to model and solve optimization problems. BLP is a type of linear programming that uses Boolean variables, which can take on only two values, 0 or 1. The objective of BLP is to find a set of values for the Boolean variables that satisfy a set of linear constraints and optimize an objective function. The objective function is typically a linear combination of the Boolean variables, and the constraints are linear inequalities or equalities. BLP has several advantages over traditional linear programming techniques. First, BLP can model problems that involve binary decisions, such as yes/no decisions or on/off decisions. Second, BLP can handle problems with a large number of variables and constraints, which makes it suitable for solving complex optimization problems. Third, BLP can be solved efficiently using specialized algorithms, such as branch-and-bound or cutting-plane algorithms (Akutsu, 2018; Cobham et al., 1961; Mezentsev, 2016; Papadimitriou & Steiglitz, 1998).

Given set $I = \{1,2,\ldots,m\}$ as places where facilities (cluster center) can be found, $J = \{1,2,\ldots,n\}$ as clients (cluster points) with unit requests in each where the client is, the non-negative cost matrix $C = [c_{ij}]$ for moving each $j \in J$ from each $i \in I$, and p is the number of facilities to be opened, then the Boolean Linear Programming formulation of PMP can be written as follows :

$$min \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} x_{ij} \tag{1}$$

With constraint:

$$\sum_{i=1}^{m} x_{ij} = 1, j = 1,\ldots,n \tag{2}$$

$$\sum_{i=1}^{m} \overline{y_i} = p \tag{3}$$

$$x_{ij} \le \overline{y_i}, i = 1,\ldots,m;\ j = 1,\ldots,n \tag{4}$$

$$\overline{y_i} \in \{0,1\}, i = 1,\ldots,m \tag{5}$$

$$x_{ij} \in \{0,1\}, i = 1,\ldots,m;\ j = 1,\ldots,n \tag{6}$$

The constraints Equation (2) determines that each client must be served by one facility. Equation (3) states that p is an open facility. Equation (4) constraints prevent clients from being served by closed facilities. For each feasible solution in Equation (5) and Equation (6), $\overline{y_i} = 1$ if facility i is open, and $\overline{y_i} = 0$, otherwise; $x_{ij} = 1$ if client j is served by facility i, and $x_{ij} = 0$, vice versa.

The PMP example is described by an m × n matrix that is $C = [c_{ij}]$ and $1 \le p \le |I|$. It is assumed that the entries in C are non-negative and finite, namely $C \in \mathbb{R}_+^{mn}$. If $I = J$, then the model becomes ReVelle and Swain's classic PMP model with n^2 Boolean decision variables.

Diet Menu Problem in General

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In general, the mathematical of diet menu problem model is formed as follows (Pichugina, 2020):

Given n constituent foodstuffs $\{P_1, P_2, \dots, P_n\}$. Let x_j be the foodstuff that are used daily so that $P_j\{j \in J_n = (1, \dots, n)\}$. Then the vector $x = (x_j) j \in \mathbb{R}^n$ is the daily diet formulation. Suppose there are m different food components $\{N_1, N_2, \dots, N_m\}$, and the number of food components N_i as a_{ij} so that $P_j(i \in J_m, j \in J_n)$. Thus, the total number of the food components N_i can be formulated as $\sum_{j=1}^{n} a_{ij} x_j$, $i \in J_m$ in this diet. An optimal diet is a combination of the daily number of foods consumed and the daily need for food components is met, and the minimum function (cost) is achieved and limits are maintained. Therefore, the objective function is in the form of a linear program and can be expressed as a diet menu problem model formed as follows:

$$minimize\ W = \sum_{j=1}^{n} c_j x_j \tag{7}$$

Constraint to:

$$x_j \leq d_j, j \in J_n \tag{8}$$

$$\overline{p_j} \leq x_j \leq \overline{\overline{p_j}},\ j \in J_n \tag{9}$$

$$\sum\nolimits_{j=1}^{n} a_{ij} x_j \geq b_i,\ i \in J_m \tag{10}$$

$$b_i \leq \sum\nolimits_{j=1}^{n} a_{ij} x_j \leq \overline{b_i},\ i \in J_m \tag{11}$$

Where,

c_j	= cost a unit of the foodstuff P_j
x_j	= be the foodstuff that are used daily.
d_j	= available number of the foodstuff P_j.
$[\overline{p_j}, \overline{\overline{p_j}}]$	= the range of the number of the products P_j consumed where $\overline{p_j} \geq 0$.
a_{ij}	= units of the foodstuffs $P_j(i \in J_m, j \in J_n)$ that contain the number of food component N_i.
$[b_i, \overline{b_i}]$	= the range for the number of the food components N_i allowed in daily needs.

METHODOLOGY

The methodology used in this study is to use the library method, namely by collecting, reading, and studying journal references, related books and information obtained from the internet. The stages of establishing a diet menu problem model based on the Boolean Linear Programming approach are carried out as follows: examine the problem, determine the notations, indexes, parameters, and decision variables to form a diet menu problem model, determine the objective function in the diet menu problem model, where in this function model the goal is to minimize costs, determine the constraints related to the diet menu problem, establish a model of the diet menu problem by applying the Boolean Linear Programming formulation which is formulated in the form of an integer linear programming (Integer Linear Programming), modified and expanded which aims to cover a varied management range of daily diet menus and meet daily nutritional needs while minimizing costs.

RESULT AND DISCUSSION

Now, the diet menu problem model with Boolean Linear Programming approach is built as follows:

TABLE 1. The Notations of Diet Menu Problem

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Notation	Description
$\{D_i\}_{i\in J_I}$	Types of dishes (main dishes, appetizers, dessert, salads, drinks, soups, etc).
$\{M_j\}_{j\in J_J}$	Types of ingestions/mealtimes (supper, breakfast, dinner, lunch, etc).
$R_i = \{R_{i,k_i}\}k_i \in J_{K_i}$	A set of the dishes D_i-recipes, $i \in J_I$.
$\{P_l\}_{l\in J_L}$	A set of the foodstuffs.
$\{I_m\}_{m\in J_M}$	A set of the food components: nutrients (carbohydrates, proteins, total lipid/fat, sugar, water), minerals (calcium, magnesium, iron, etc), vitamins, lipids, amino acids.

TABLE 2. The Indices of Diet Menu Problem Model

Index	Description
$i \in J_i$	Dishes
$j \in J_j$	Mealtimes
$k_i \in J_{k_i}$	Recipes
$l \in J_l$	Foodstuffs
$m \in J_m$	Food Components

TABLE 3. The Parameters of Diet Menu Problem Model

Parameter	Description
c_l	Cost of a unit of the foodstuffs P_l (l).
a_{lik_i}	The number of the foodstuffs P_l in a portion of the dish D_i cooked according to the recipes R_i $(l,\ i,\ k_i)$.
d_{lm}	The number of the components I_m in a unit of the foodstuff P_l (l, m).

A set of decision variables for each combination (i, j, k_i) as follows:

$$x_{ijk_i} = \begin{cases} 1,\ the\ dish\ D_i\ for\ the\ meal\ M_j\ is\ prepared\ by\ a\ recipe\ R_{k_i} \\ 0,\ otherwise \end{cases} \tag{12}$$

If y_l is denoted as the amount of food ingredients aimed at minimizing costs, then Equation (7) can be written as follows:

$$min\ W = \sum_{l=1}^{L} c_l y_l \tag{13}$$

Then if equation (13) is expressed in the form of Equation (12), then $\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k_i}^{K_i} a_{lik_i}.x_{ijk_i}, \forall l$ is the total number of P_l in the menu. Because of that,

$$y_l = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k_i}^{K_i} a_{lik_i}.x_{ijk_i}, \forall l \tag{14}$$

Substituting the variable y_l in the form of a general mathematical model of the diet menu problem (7), the objective function and its constraints are written as follows:

$$minimum\ Z = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k_i}^{K_i}\left(\sum_{l=1}^{L} c_l\,.\,a_{lik_i}\right).x_{ijk_i} \tag{15}$$

Constraints related to the diet menu problem is written as follows:

1. Constraints of rules on food components consumed. Constraint of equation (11) will be formalized.

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$$b_m = \sum_{l=1}^{L} d_{lm} . y_l = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k_i}^{K_i} \left(\sum_{l=1}^{L} a_{lik_i} . d_{lm} \right) . x_{ijk_i} \quad (16)$$

is the number of the components I_m for each daily menu m. Remind that the equation:

$$R_{ik_im} = \sum_{l=1}^{L} a_{lik_i} . d_{lm} \quad (17)$$

represent a number of components I_m for each daily recipe R_{k_i} of the dish D_i. Then, the equation (16) is reformed as follows:

$$b_m = \sum_{l=1}^{L} d_{lm} . y_l = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k_i}^{K_i} R_{ik_im} . x_{ijk_i} \quad (18)$$

2. Limitations of the number of foodstuffs in the menu. The lower and upper limits of the number of the foods P_l per day are represented by $\overline{p_l}$, $\overline{\overline{p_l}}$
3. The presence of several dishes is mandatory in the diet. The set of indices of mandatory dishes in the meal $M_j, \forall j$ is denoted by $A_{ij} = \left\{ i_i^{(j)} \right\} \subseteq J_I$
4. The amounts of the mealtimes of certain types of dishes in daily limits. The lower and upper limits of the amounts of mealtimes M_j of the types D_i- dishes per day, are represented by $\overline{S_\iota}, \overline{\overline{S_\iota}}$. Then, the notation of the total number D_i-mealtime per day is S_i and representable by:

$$S_i = \sum_{j=1}^{J} \sum_{k_i}^{K_i} x_{ijk_i}, \forall i \quad (19)$$

5. The daily menu contains variety of foods. The requirement on variety of foods is limited.
6. If a diet is being implemented, it is mandatory to have certain dishes cooked according to the prescribed recipes/forbidden of using certain recipes in a day. Then, the following notations will be used:
   - $D_i = \left\{ k_1^{(i)}, k_2^{(i)}, \dots, k_{q^{(ij)}}^{(i)} \right\} \subseteq J_{K_i}$ is a set of indices of the D_i type of dish during a day using mandatory recipes;
   - $D_i' = \left\{ k_1'^{(i)}, k_2'^{(i)}, \dots, k_{q'^{(i)}}'^{(i)} \right\} \subseteq J_{K_i}$ is a set of indices of the D_i type of dish during a day using forbidden recipes;
7. It is mandatory to have certain dishes cooked according to the prescribed recipes/forbidden of using a spesicific recipe in a meal $M_j, \forall j$. Then, the notations that will be used are presented by:
   - $B_{ij} = \left\{ k_1^{(ij)}, k_2^{(ij)}, \dots, k_{q^{(ij)}}^{(ij)} \right\} \subseteq J_{K_i}$ is a set of meal indices M_j, i, j and the D_i type of dish using mandatory recipes;
   - $B_{ij}' = \left\{ k_1'^{ij}, k_2'^{ij}, \dots, k_{q'^{ij}}'^{ij} \right\} \subseteq J_{K_i}$ is a set of meal indices M_j, i, j and the D_i type of dish using forbidden recipes;

Then, a new parameter is created, namely:

$$g_{ik_i} = \sum_{l=1}^{L} c_l . a_{lik_i} \quad (20)$$

For each serving of dish D_i prepared with recipe P_{k_i} $(\forall i, k_i)$, so Equation (15) can be changed to:

$$minimum\ Z = \sum_{i=1}^{I} \sum_{j=1}^{J} g_{ik_i} \sum_{k_i}^{K_i} x_{ijk_i} \quad (21)$$

Subject to:

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$$\overline{b_m} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k_i}^{K_i} R_{ik_im}.x_{ijk_i} \le \overline{\overline{b_m}},\ \forall m \tag{22}$$
$$\overline{p_l} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k_i}^{K_i} a_{lik_i}.x_{ijk_i} \le \overline{\overline{p_l}},\ \forall l \tag{23}$$
$$\sum_{k_i=1}^{K_i} x_{ijk_i} = 1,\ i \in A_j\ ,\forall j \tag{24}$$
$$\overline{S_\iota} \le \sum_{j=1}^{J}\sum_{k_i}^{K_i} x_{ijk_i} \le \overline{\overline{S_\iota}},\ \forall i \tag{25}$$
$$\sum_{j=1}^{J} x_{ijk_i} \le 1,\ \forall k_i,\ \forall i \tag{26}$$
$$\sum_{j=1}^{J} x_{ijk_i} \ge 1,\ k_i \subseteq D_i,\ \forall i \tag{27}$$
$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k_i \in D_i'} x_{ijk_i} = 0 \tag{28}$$
$$x_{ijk_i} = 1,\ k_i \in B_{ij},\ \forall i,\ j. \tag{29}$$
$$x_{ijk_i} = 0,\ k_i \in B_{ij}',\ \forall i,\ j. \tag{30}$$

Where,

g_{ik_i} = the cost of the foodstuffs P_l
R_{ik_im} = the number of the food components I_m of recipe R_{k_i} of the dish D_i.
x_{ijk_i} = the set of decision variables for each combination (i, j, k_i)
$\overline{b_m}, \overline{\overline{b_m}}$ = the limitations of the number of the food components I_m in the menu, respectively.
$\overline{p_l}, \overline{\overline{p_l}}$ = the limitations of the number of the foodstuffs, respectively.
$\overline{S_\iota}, \overline{\overline{S_\iota}}$ = the limitations of the amount mealtimes of the D_i-dishes daily type.
D_i = the D_i type of dish for a day using mandatory recipes.
D_i' = the D_i type of dish for a day using forbidden recipes.
B_{ij} = the meal M_j, i, j and the D_i type of dish using mandatory recipes.
B_{ij}' = the meal M_j, i, j and the D_i type of dish using forbidden recipes.

The objective function in Equation (21) aims to minimize the total costs needed to meet the daily number of foodstuffs and food components. Equations (22) to (30) are some of the constraints related to the Diet Menu Problem. On the one hand, domain (12), (24), (27)-(30) can be viewed as a Boolean set (12) that must be satisfied by additional constraints. On the other hand, it can also be written as an intersection of a Boolean permutation and a partial permutation set (Pichugina & Yakovlev, 2020, 2019). Therefore, applying an algorithm that solves his DMP properties on this set, we can expect to get a solution with higher accuracy than any method known so far.

CONCLUSION

In linear programming applications, especially integer programming, the diet menu problem model already covers a large scope, but it still needs some additions to the decision variables by applying the Boolean Linear Programming formulation, so that it covers large and varied dimensions by focusing on consumption time. The Diet Menu Problem Model with the Boolean Linear Programming approach can determine a combination of food menus (food ingredients) that meet daily nutritional needs (food components) with a varied menu where this model can determine mandatory menus and forbidden menus at the time of consumption (Boolean sets), as well achieving the minimum objective function (cost) and the constraints related to the diet menu are met. However, applying the diet menu problem model with the Boolean Linear Programming approach to real-world problems is very difficult to solve optimally because it covers a large and varied scope and can determine mandatory menus and prohibited menus.

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