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A Linear-Programming-Based Study for Snack Selection to Minimize Sugar Intake among Middle School Students

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Abstract. Excessive sugar intake among teenagers has become a growing public health concern. High-sugar snacks in campus stores are a major contributor to adolescent obesity and other related health problems. This study establishes a mixed-integer linear programming model to minimize the total sugar content of snack selections for middle school students, subject to constraints on budget, energy, protein, preference, and diversity, aiming to provide a practical and acceptable strategy to choose snacks for students. An optimal solution is obtained in a real case study based on data collected from a campus store in Beijing, covering 16 types of snack and beverage products. To examine the robustness of the model, a one-factor-at-a-time sensitivity analysis is conducted. The analysis shows how changes in key parameters affect the optimal solution and reveals trade-offs between sugar control and factors such as budget, snack variety, and preference requirements. These results provide practical strategies for students to reduce sugar intake according to their priorities among taste, budget, and health.

Keywords: mixed-integer linear programming, one-factor-at-a-time sensitivity analysis, snack selection, campus store, sugar intake, adolescent health

1. Introduction

Adolescent obesity has received increasing attention in recent years. High-sugar snacks and beverages are widely available in campus stores [1, 2]. Excessive sugar consumption has been linked to several health problems, including obesity, type 2 diabetes, and dental caries [3]. Therefore, the food available in campus stores is worth considering when discussing healthier snack choices.

The idea of optimizing food choices with mathematical methods is not new. One of the best-known examples is the classical diet problem formulated by Stigler, which seeks a combination of foods that satisfies nutritional requirements at the lowest possible cost [4, 5]. The original problem reflected the concerns of that period: food shortages and nutritional deficiencies.

The purpose of diet optimization has since become broader. In addition to meeting basic nutritional requirements and controlling cost, researchers have considered objectives related to

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health and overall dietary quality, such as sugar intake and nutritional balance. In this study, this idea is applied to snack purchases in a campus store.

While classical diet models focus on minimizing cost, our model uses sugar intake as the main objective. At the same time, snack choices are affected by other factors, including budget, energy and protein requirements, student preference ratings, and snack diversity. We therefore include these factors as constraints in the model. Moreover, snacks are sold in whole packs, so the quantity of each snack is considered as an integer variable [6].

The model is tested using data collected from a campus store in Beijing and the resulting mixed-integer linear programming problem is solved in Python. On this basis, a sensitivity analysis is conducted to examine how the optimal solution changes when the budget, required snack variety, and preference requirements are varied.

2. Mathematical model construction

2.1. Problem description

Students choosing snacks from a campus store do not make their decisions based on sugar content alone. Price, nutritional content, personal preference, and the variety of products selected may all affect the final choice. We therefore consider the following snack-selection problem.

Suppose that the campus store offers n types of snacks. Each snack has a given price, calorie content, protein content, sugar content, and preference rating. The objective is to choose a combination of these snacks with the lowest total sugar intake while satisfying requirements for budget, energy intake, protein intake, student preference, and snack diversity.

This problem is formulated as a mixed-integer linear program. The resulting model determines how many packages of each snack should be selected while satisfying all of the specified constraints.

2.2. Notations

The notations used in this paper are summarized in Table 1.

Table 1. Summary of notations

Symbol	Definition
n	Number of snack types.
i	Index of snack types, $i=1,2,\ldots,n$.
x_i	Integer variable, quantity of snack i selected, $x_i \in Z_{\geq 0}$.
y_i	Binary variable, $y_i=1$ if snack i is selected, otherwise $y_i=0$.
s_i	Sugar content of snack i.
c_i	Price (cost) of snack i.
e_i	Energy (calorie) content of snack i.
p_i	Protein content of snack i.
r_i	Preference rating of snack i.
C_{max}	Upper bound of total cost.
E_{max}	Upper bound of total energy intake.
E_{min}	Lower bound of total energy intake.

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Table 1. (continued)

P_{min}	Minimum required protein intake.
R_{min}	Minimum required total preference rating.
K	Minimum number of different snack types to be selected.
M	A sufficiently large constant used in the linking constraints.

2.3. Objective function

The snack selection model constructed in this paper aims to minimize the total sugar intake of the selected snacks. Let x_i denote the quantity of snack i selected, and s_i denote the sugar content of snack i. Since the snacks are sold in whole packs, x_i should be an integer variable. The total sugar intake can be expressed as $\sum_{i=1}^{n} s_i x_i$. Therefore, the objective function is formulated as:

$$min \ \sum_{i=1}^{n} s_i x_i \tag{1}$$

where n is the total number of snack types. The model aims to determine the optimal solutions x_i that minimize the objective function, subject to the constraints presented in Section 2.4.

2.4. Model constraints

This problem is subject to nutritional, budgetary, preference, and diversity constraints. These constraints make sure that the selection of snacks is not only low in sugar but also acceptable in cost, energy, and taste. The constraints are formulated as follows.

2.4.1. Cost constraint

The total cost of the selected snacks should not exceed the given budget $C_{\max}$, so the constraint is formulated as:

$$\sum_{i=1}^{n} c_i x_i \leq C_{max} \tag{2}$$

where c_i is the price of snack i.

2.4.2. Energy constraints

The total energy intake should remain in a reasonable range, so that students can get sufficient energy from the snacks without exceeding the recommended upper limit. As a result, the constraints are formulated as:

$$\sum_{i=1}^{n} e_i x_i \leq E_{max} \tag{3}$$

$$\sum_{i=1}^{n} e_i x_i \geq E_{min} \tag{4}$$

where e_i is the energy (calorie) content of snack i, and $E_{\max}$ and $E_{\min}$ are the upper and lower bounds of total energy intake, respectively.

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2.4.3. Protein constraint

To provide the students with enough protein, the minimum protein intake constraint is set, formulated as:

$$\sum_{i=1}^{n} p_i x_i \geq P_{min} \tag{5}$$

where p_i is the protein content of snack i and $P_{\min}$ is the lower bound of total protein intake.

2.4.4. Preference constraint

To guarantee that the selection we made is acceptable to students, the total preference rating should not be lower than a given threshold R_{min}, so we get the constraint:

$$\sum_{i=1}^{n} r_i x_i \geq R_{min} \tag{6}$$

where r_i is the preference rating of snack i.

2.4.5. Diversity constraints

If we only have the constraints described above, the optimal solution may select only a few types of snacks. However, most people prefer a selection with various snacks, so the diversity constraints are added.

We define $y_i \in \{0,1\}$ as a binary indicator variable, where $y_i = 1$ if snack i is purchased, and $y_i = 0$ otherwise. Then, the diversity constraint should be:

$$\sum_{i=1}^{n} y_i \geq K \tag{7}$$

where K denotes the minimum number of different snack types to be selected.

Moreover, to link the variables x_i and y_i, we have another constraint formulated as:

$$y_i \leq x_i, \ \forall i \in \{1, \ldots, n\} \tag{8}$$

$$x_i \leq M y_i, \ \forall i \in \{1, \ldots, n\} \tag{9}$$

where M is a sufficiently large constant.

Constraint (8) ensures that if the purchase quantity of snack i is 0 ($x_i = 0$), y_i must be 0 and if snack i is selected ($y_i = 1$), x_i must be greater than or equal to 1. Constraint (9) ensures that if snack i is not selected ($y_i = 0$), x_i must be 0 and if the purchase quantity of snack i is greater than 0 ($x_i \geq 1$), y_i must be 1. These two constraints ensure that $y_i = 0 \Leftrightarrow x_i = 0$ and $y_i = 1 \Leftrightarrow x_i \geq 1$.

3. Case study

3.1. School snack data collection

The data used in this study were collected from a campus store in a secondary school in Beijing, China. 16 snack products were collected, including 6 beverages and 10 snacks (biscuits, wafers,

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pies, and pastries). We selected both higher-sugar and lower-sugar products to ensure category diversity in the optimization model.

The product information included three items: name, package size, and price. We obtained the information through on-site shelf inventory at the convenience store. The nutrition data, such as sugar content and calories, were extracted from the nutrition facts labels on product packaging. For each product, the sugar content (g), calories (kcal), and protein content (g) were recorded per 100 mL for beverages or per 100 g for snacks, and then converted to total sugar and total calories per package.

The formulas we used for conversion are as follows:

Beverages: Total sugar = Sugar (per 100 mL) × (Size in mL ÷ 100);

Snacks: Total sugar = Sugar (per 100 g) × (Size in g ÷ 100);

Total calories and protein were calculated in the same way.

We also collected preference data through an online questionnaire and distributed it through WeChat groups to students in grade 7 to 12. Respondents were asked to rate each of the 16 products on a 1-10 scale (1 = "would never buy", 10 = "would definitely buy"). We instructed respondents to assume that all products had the same price, which eliminated price as a confounding factor and ensured that the preference scores purely reflected taste preference.

After processing, the final dataset contains 16 products, with each observation including: product name, package size, total sugar (g), total calories (kcal), total protein (g), price (CNY), and average preference rating, as shown in Table 2.

Table 2. Data of products

Product name	Package size (mL/g)	Sugar (g)	Calorie (kcal)	Protein (g)	Preference rating	Price (CNY)
Uni-President 500ml Lemon Flavored Iced Tea	500	46	190	0	4.22	3.36
Lemon Republic 470ml Misty Sugar-Tangerine Compound Juice Drink	470	51.7	207	0	2.91	5.76
Minute Maid 450ml Pulp Orange Juice Drink	450	42.3	180	0	4.34	3.36
JDB 500ml Bottled Herbal Tea (Liangcha)	500	42.5	170	0	3.06	4.7
Nongfu Spring Scream 550ml Fiber-Type Lemon-Flavored Sport Drink	550	35.8	154	0	4.56	4.61
Waixingren (Alien) 600ml Low-Sugar Coconut-Flavored Electrolyte Water	600	28.8	120	0	3.28	6.24
Dali 200g French Milk-Flavored Soft Bread	200	44	680	14.4	4.63	0.98
Orion Choco Pie (2-Pack, 74g)	74	28.1	325.6	3.034	5.81	3.55
Maidajie 70g Two-Piece Pork-Floss Mooncake	70	19.6	294	5.46	4	4.03
Orion 48g Choco Boy Chocolate Cookies	48	16.8	226	3.12	5.75	4.7
Danfu 40g Butter Waffle	40	10.4	152	2.4	4.13	3.74
Bourbon 56g Puchi Crunchy Cocoa Cookies	56	17.9	274	2.632	5.19	4.61
Bami 80g Dorayaki (Taro-Paste & Mochi Flavor)	80	19.2	288	4.24	3.66	5.66
Moxiao Yan 45g Jasmine-Tea Cookies	45	11.3	167	2.25	4.25	3.36
Chips Ahoy! 85g Rich Chocolate Crispy Cookies	85	27.2	408	4.76	6.5	6.24
Master Kong 3+2 Lemon-Flavored Soda Sandwich Cookies 50g	50	15	225	3.1	4.13	2.78

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3.2. Parameter settings

The parameters used in the case study are summarized in Table 3.

Table 3. Parameter settings

Parameter	Value	Description
C_{max}	18 CNY	Upper bound of total cost.
E_{max}	1000 kcal	Upper bound of total energy intake.
E_{min}	300 kcal	Lower bound of total energy intake.
P_{min}	10 g	Minimum required protein intake.
R_{min}	18	Minimum required total preference rating.
K	3	Minimum number of different snack types to be selected.
M	20	A sufficiently large constant used in the linking constraints.

Since middle school students usually have a limited budget for snacks, we set $C_{\max} = 18\ CNY$. The energy upper bound is set to $E_{\max} = 1000\ kcal$. This is not a nutritional recommendation, but a scenario parameter representing a relaxed purchasing situation, which allows the model to obtain feasible solutions. The energy lower bound $E_{\min} = 300\ kcal$ is set based on the daily energy requirements of adolescents, corresponding to a reasonable proportion for an afternoon snack [7]. The protein lower bound $P_{\min} = 10\ g$ is set following the recommendation that adolescents should choose protein-rich snacks such as dairy products and nuts [8]. In addition, we set $R_{\min} = 18$ and $K = 3$, guaranteeing that the selection of snacks is acceptable for students. Finally, we set $M = 20$, because with 18 CNY, at most 18 packs of the cheapest item in the store can be purchased.

3.3. Computational results and analysis

According to the data collected in Section 3.1 and parameters set in Section 3.2, we coded this mixed-integer programming model in Python and solved it. The model selects 1 pack of Orion 48g Choco Boy Chocolate Cookies, 2 packs of Danfu 40g Butter Waffle, and 1 pack of Moxiao Yan 45g Jasmine-Tea Cookies.

All constraints can be verified from the result: the total cost is 15.54 CNY, the total calorie content is 697.0 kcal, the total protein content is 10.17 g, and the total preference rating is 18.26. All of them meet the requirements. In addition, the model selects 3 types of snacks, which satisfies the diversity constraints. As a result, this solution is feasible.

The minimum sugar intake in this case is 48.9 g. However, the World Health Organization recommends limiting free sugar intake to less than 10% of total energy intake, with a further reduction to 5% or less suggested for additional health benefits [9]. Similarly, Chinese Nutrition Society suggests that the daily intake of added sugar should be controlled within 25 grams and should not exceed 50 grams at most [10]. It should be noted that this study measures total sugar based on product labels rather than free or added sugar specifically. Therefore, the reported 48.9 g of total sugar cannot be directly compared with these recommendations Nevertheless, the result shows that the selected snack combination contains a substantial amount of total sugar.

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4. Sensitivity analysis

4.1. Sensitivity analysis of C_{max}

The cost upper bound $C_{\max}$ directly determines how much students can spend on snacks. We therefore examine how changes in the budget affect the minimum sugar intake.

In this analysis, $C_{\max}$ is varied from 10 CNY to 30 CNY with a step size of 1 CNY, while all other parameters and data on snacks remain unchanged. The model is solved in Python, and the results are shown in Figure 1.

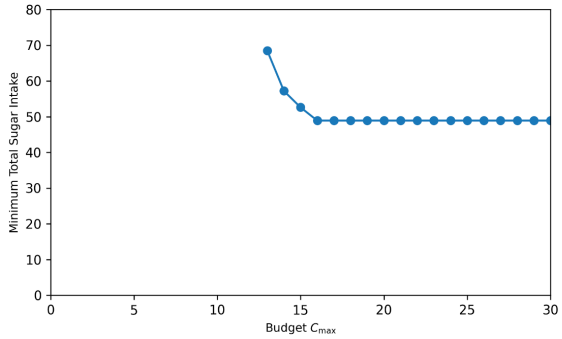


Figure 1. Relationship between minimum total sugar intake and C_{max}

Figure 1 shows that the model is infeasible when $C_{\max}$ is 12 CNY or less. As $C_{\max}$ increases from 13 CNY to 16 CNY, the minimum total sugar intake decreases sharply from about 70 g to about 49 g. However, when $C_{\max}$ exceeds 16 CNY, the total sugar intake does not change as $C_{\max}$ increases. This result suggests that with a larger budget, lower-sugar snack combinations become feasible, so the minimum total sugar intake decreases. Beyond 16 CNY, further increases in the budget do not improve the solution, because no combination with less sugar exists within the current scenario.

4.2. Sensitivity analysis of K

The diversity parameter K controls the minimum number of different snack types to be selected. A larger K requires the solution to include more snack types, which may increase total sugar intake while making the selection more varied.

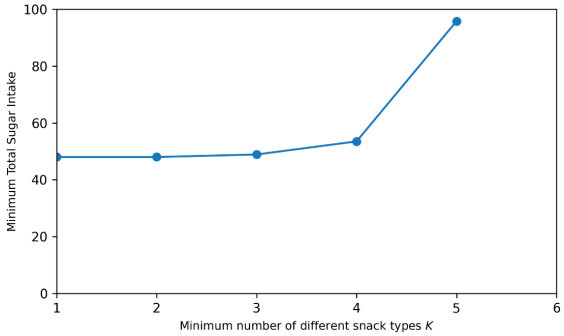


Figure 2. Relationship between minimum total sugar intake and K

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In this analysis, K is varied from 1 to 6 with a step size of 1, while all other parameters and data on snacks remain unchanged. The model is solved in Python, and the results are shown in Figure 2.

As shown in Figure 2, when $1 \leq K \leq 4$, the minimum total sugar intake rises slowly as K increases. When $K = 5$, the minimum total sugar intake increases sharply, which means that although a feasible solution still exists, the minimum total sugar intake becomes much higher. When $K \geq 6$, there is no feasible solution. The results therefore show a trade-off between snack variety and sugar control.

4.3. Sensitivity analysis of R_{min}

The preference parameter $R_{\min}$ determines the minimum total preference rating that the solution must achieve. A higher $R_{\min}$ imposes a stronger preference requirement, which may increase the total sugar intake.

In this analysis, $R_{\min}$ is varied from 0 to 25 with a step size of 1, while all other parameters and data on snacks remain unchanged. We use Python to solve the problem and visualize the data. The results are shown in Figure 3.

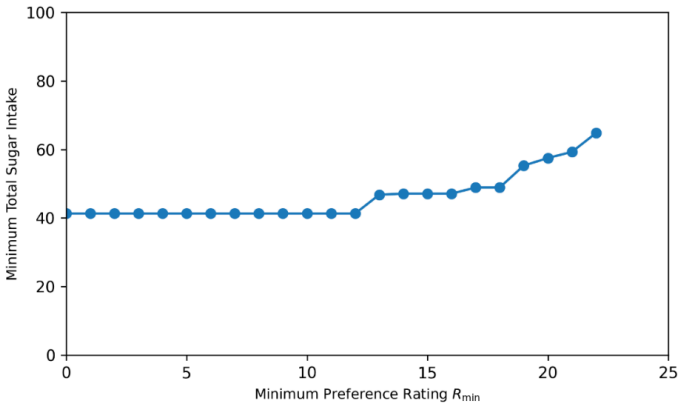


Figure 3. Relationship between minimum total sugar intake and Rmin

As shown in Figure 3, when $R_{\min} \leq 12$, the minimum total sugar intake remains unchanged at about 41 g. This is because the preference constraint is not tight. When $R_{\min} \geq 13$, the minimum total sugar intake increases as $R_{\min}$ increases. This result suggests a clear trade-off between preference requirement and sugar control.

5. Conclusions

In this study, we used the classical diet problem as a starting point and applied it to snack selection in a campus store. The model was built as a mixed-integer linear program with constraints on budget, energy, protein, preference, and snack variety.

Using data collected from a campus store, the model identified a feasible snack combination that minimizes total sugar under the given constraints. The solution consists of 1 pack of Orion 48g Choco Boy Chocolate Cookies, 2 packs of Danfu 40g Butter Waffle, and 1 pack of Moxiao Yan 45g Jasmine-Tea Cookies. These products contain 48.9 g of sugar in total. This amount is still relatively high, even though the combination gives the lowest sugar intake among the feasible options in our

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model. In other words, choosing from the products currently available in the store may not be enough to reduce sugar intake to a low level.

We also examined how the solution changed when key parameters were varied. Increasing the budget initially allowed the model to select combinations with less sugar. However, once the budget passed a certain level, further increases did not reduce the minimum sugar content within the current product set. Moreover, trade- offs can be seen with snack variety and preference. Requiring more snack types or a higher total preference score increased the minimum sugar content in the scenarios we tested. These findings suggest that sugar reduction needs to be considered alongside budget, variety, and preference requirements.

There are several possible directions for further study.

First, the model could consider more nutritional factors in future work. We did not include food additives or sugar substitutes in this study because our dataset did not contain quantitative information about them. If such data become available, we could consider adding these factors as further constraints or objectives in the model.

Second, we could collect data from more campus stores as well as stores outside schools. This would allow us to compare the snack options available at different locations and see whether some stores offer more low-sugar choices than others. The results could also be useful when considering which types of products campus stores should stock.

Third, future studies could optimize sugar content, cost, and preference simultaneously using a multi-objective approach. An important challenge would be choosing appropriate weights, because different groups may assign different priorities to these factors. For example, students may place greater importance on taste, while nutrition professionals may prioritize limiting sugar intake. Collecting weighting information from different stakeholders would make it possible to compare how the resulting trade-offs vary across groups.

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