Optimizing Nutritional Meal Logistics for School Programs

Problem Statement

The rise in sedentary lifestyles and diet-related health issues such as obesity, diabetes, and heart disease among children highlights the urgent need for affordable, nutritious school meals. School meal programs face challenges like budget limitations, varying student food preferences, and the need to comply with strict nutritional standards. Addressing these challenges is essential to support healthy growth, development, and long-term well-being for students aged 9-12.

Possible Scenarios

The diet optimization model developed in this project has applications beyond schools. It can be used in public health programs to design cost-effective community feeding initiatives, in healthcare settings to create tailored diets for children with specific health conditions, and in disaster relief efforts to provide affordable, nutritionally balanced meals for shelters. Policymakers can also use it to establish practical dietary standards, while researchers can apply it to study personalized nutrition for children.

Specific Scenario

This project focuses on applying the model to school meal programs for students aged 9-12, following USDA nutritional guidelines. The model is designed to minimize the cost of daily meals while meeting essential nutritional requirements, helping schools create balanced, affordable meal plans. By addressing real-world constraints such as budget limitations and compliance with dietary standards, the model supports healthier eating habits, reduces health disparities, and enhances student well-being.

Data Sources

To develop the diet optimization model, we utilized data from three key sources to ensure accuracy and applicability:

1. **Nutritional Data:** Nutritional information was obtained from the Kaggle dataset titled "Emoji Diet Nutritional Data SR28." This dataset provides a comprehensive breakdown of nutrients for various food items, including macronutrients (calories, carbohydrates, protein, fats), micronutrients (vitamins and minerals), and other dietary components like fiber and cholesterol. Data Link

2. **Cost Data:** Pricing information for food items was sourced from the Bureau of Labor Statistics (BLS) Average Retail Food and Energy Prices dataset. This dataset provides

average retail prices for commonly consumed food products, enabling the model to factor in real-world cost considerations. Cost Data Link

3. **USDA Guidelines:** Nutritional benchmarks were drawn from USDA guidelines, which outline recommended daily intakes for students aged 9-12. These guidelines specify the required levels of calories, macronutrients, and micronutrients, forming the constraints for the model. USDA Guidelines Link

Optimization Model Formulation

Objective Function:

Minimize the total cost of the diet:

Minimize $Z=\sum_{d=1}^{5} \quad \sum_{i=1}^{n} \quad c_i.x_{id}$

Where:

- c_i = Cost per serving of food item
- x_{id} = Binary decision variable for food item i on day d, where x_{id} =1 if the item is included, and x_{id}= 0 otherwise
- n = number of food items (52 in this case)
- d = day of the week (1 to 5)

Decision Variables:

- x_1…….x_n Binary variables representing whether each food item is selected (x_i=1) or not (x_i = 0)

Constraints:

1. Nutritional Constraints

The selected food items must collectively meet or exceed the minimum required values for key nutrients:

$max_j <= \sum_{i=1}^{n} \quad a_{ij}.x_i >= min_j$

- a_{ij} = the amount of nutrient j provided by one unit of food item i
- max_j = the maximum required intake of nutrient j
- min_j = the minimum required intake of nutrient j

- Where for each nutrient j (Calories (kcal), Protein (g), Total Fiber (g), Vitamin A (IU), Vitamin C (mg), Calcium (g), Iron (mg))

650 ≤ Calories (kcal) ≥ 950

Protein (g) ≥ 12

Total Fiber (g) ≥ 5

Vitamin A (IU) ≥ 350

Vitamin C (mg) ≥ 20

Calcium (g) ≥ 3.6

Iron (mg) ≥ 4

2. Category Constraints

Ensure exactly one item is selected from each category:

$\sum \quad x_{ig} = 1$

Where g represents the Categories: Beverages, Dessert, Fruit, Main, Meat, Snack and Vegetables.

3. Budget Constraint

Ensure the total cost does not exceed the specified budget ($30 per student for 5 trays for 75 students). Total budget for the whole week is $2,250.

$\sum_{i=1}^{n} \quad c_i . x_i \leq C$

4. Binary Decision Variables

All decision variables x_i are binary, indicating whether a food item is selected (whether each food item is selected (x_i=1) or not (x_i = 0)

$x_i \in \{0,1\}$

5. Non-Negativity Constraints:

The quantities of food items must be non-negative. Therefore:
$x_i > 0$

6. Non-Repetition Constraint

This constraint ensures that if an item is selected for a day, it cannot be selected for any subsequent days in the week.

$$x_{id} + \sum_{k=1}^{d-1} x_{ik} \leq 1$$

Results

Our Models generated four lunch trays, each meeting USDA nutritional requirements while minimizing costs.

Lunch Tray 1:
    Selected items: ['milk', 'doughnut', 'tangerine', 'rice', 'egg', 'popcorn', 'carrot']
    Cost for one tray: $0.98
    Cost for 75 students: $73.50

Lunch Tray 2:
    Selected items: ['milk', 'cookie', 'kiwifruit', 'spaghetti', 'bacon', 'bread', 'corn']
    Cost for one tray: $1.30
    Cost for 75 students: $97.50

Lunch Tray 3:
    Selected items: ['milk', 'pancakes', 'banana', 'pizza', 'chicken', 'peanuts', 'hot pepper']
    Cost for one tray: $2.24
    Cost for 75 students: $168.00

Lunch Tray 4:
    Selected items: ['milk', 'candy', 'grapes', 'hotdog', 'beef', 'croissant', 'potato']
    Cost for one tray: $3.10
    Cost for 75 students: $232.50

Total cost for all trays for 75 students: $571.50

To generate vegetarian lunch trays, the initial tray options were modified by removing the "Meat" category to accommodate dietary restrictions. Excel Solver was utilized to optimize the selection of vegetables as the primary decision variables while maintaining pre-selected items from the remaining categories, including Beverages, Desserts, Fruits, Main, and Snacks. The optimization objective was to minimize the total cost of the trays while adhering to USDA nutritional guidelines. Constraints were applied to ensure each tray met the required nutritional range for calories (650–950 kcal), as well as sufficient levels of protein, fiber, vitamins, and minerals. This method effectively produced cost-efficient vegetarian lunch trays that align with nutritional standards and provide variety for school students.

Vegetarian Lunch Tray 1

Items: ['milk', 'doughnut', 'tangerine', 'rice', 'eggplant', 'popcorn', 'carrot']
Cost of eggplant for 75 students: 18
Cost for 75 students: $91.5

Vegetarian Lunch Tray 2

Items: ['milk', 'cookie', 'kiwifruit', 'spaghetti', 'mushroom', 'bread', 'corn']
Cost of mushroom for 75 students: 12
Cost for 75 students: $109.5

Vegetarian Lunch Tray 3

Items: ['milk', 'pancakes', 'banana', 'pizza', 'cucumber', 'peanuts', 'hot pepper']
Cost of cucumber for 75 students: 63
Cost for 75 students: $231

Total cost for all trays for 75 students: $432

The model successfully generated four lunch trays that met USDA nutritional requirements while minimizing costs, with a total cost of $571.50 for 75 students. By modifying the initial trays to exclude meat and optimize vegetable selections, the model generated three vegetarian trays at a total cost of $432 for 75 students, ensuring inclusivity and adherence to dietary restrictions.

Challenges

1. **Limited Food Variety**

   Challenge: With only four meat options available, the "no repetition" constraint prevented the model from generating five unique lunch tray options that adhered to USDA guidelines. This reduced the flexibility of the solution and limited the variety of trays.
   Solution: To address this, we adjusted the constraints by allowing limited repetition of certain items. This provided additional flexibility while still meeting nutritional guidelines and ensuring variety in meal offerings.

2. **Excel Computational Limitations**

   Challenge: Initially, Excel struggled to handle the complexity of the model, particularly with multiple constraints and generating five lunch tray options simultaneously. Solver's computational limits hindered scalability and efficiency.
   Solution: We transitioned to using Python, which provided greater computational power and flexibility. By leveraging libraries like Pyomo, we efficiently handled complex

constraints and generated feasible solutions for all trays simultaneously. This shift reduced manual workload, improved scalability, and ensured the model was robust and accurate.

3. **Understanding Original Data and Serving Sizes**

   Challenge: The original dataset required extensive cleaning and interpretation. Serving sizes varied across food items, and aligning these with USDA nutritional guidelines was time-consuming and prone to inconsistencies.
   Solution: We conducted additional research to standardize serving sizes and cross-referenced the data with trusted sources like USDA FoodData Central. This ensured accurate calculations and alignment with nutritional requirements, enhancing the reliability of the model.

4. **Sensitivity Analysis Limitations**

   Challenge: One of the challenges we faced was the inability to generate a traditional sensitivity report for our model. Because our decision variables are binary (indicating whether a food item is selected or not), the model's feasible region is discrete rather than continuous. Sensitivity reports are typically used in linear programming models with continuous variables to analyze how changes in parameters, like costs or constraints, affect the solution. Since our model didn't meet these conditions, we couldn't use this method to evaluate the impact of parameter changes.