Family Meal Planning under COVID-19 Scarcity Constraints: A Linear Programming Approach

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Abstract The “Diet Problem” originated in the 1940s when researchers were tasked with determining the lowest-cost subsistence diet for a U.S. soldier. Originally, the task was accomplished through basic heuristics, but later the problem was solved using the simplex algorithm-the basis for modern linear programming. Enhancements to computing technology enabled further constraint consideration, including environmental and palatability constraints. In late 2019, the COVID-19 pandemic began to sweep the planet, resulting in the unavailability of staple food products in the United States, coupled with stay-at-home requirements. This study aimed to add scarcity constraints (food availability and time) to the Diet Problem to demonstrate that, even during a pandemic, healthy eating can be maintained, visits to the supermarket can be limited to reduce exposure, and this can be done relatively inexpensively. A diversified meal plan for a hypothetical family of four was identified at a total monthly cost of $641.51. This study not only demonstrates that healthy eating can be cost-effectively maintained by consumers during a global pandemic but also that shopping trips can be limited to reduce exposure and maintain social distance. Additionally, linear programming—not normally considered by academic researchers—is showcased as a methodology that can be used by other researchers to solve novel problems.

Keywords: COVID-19, diet problem, linear programming, pandemic, recommended daily allowances, scarcity, stigler

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1. Introduction

1.1. Linear Programming and Business Academic Research

In academic business publishing, similar to other fields, nearly all hypotheses are empirically tested using traditional statistical methods [1]. Over the years, many authors in the business literature-especially in the field of operations research-have used linear programming as an alternative to traditional statistical methods [2-11].

Linear optimization, also called “linear programming,” is a mathematical method for maximizing or minimizing a linear objective function given a system of linear constraints. An objective function defines the quantity to be optimized, with the purpose of determining the values of the variables that maximize or minimize the objective function without violating the constraints. This is done by first determining all the feasible solutions given the constraints (called the “feasibility region”) and then finding the optimal solution to the objective function [4]. Often, as the number of constraints is increased no solution can be found, in which case constraints can be eased systematically until a “best” solution is realized. In

1947, based upon the “input-output” methodologies of Wassily Leontief, George Dantzig identified the simplex algorithm, which is the basis for modern linear programming [12,13]. The simplex algorithm seeks to identify the optimal solution by systematically assessing each subsequent feasible solution along the edge of the feasibility region [14].

1.2. The “Diet Problem”

About a decade before Dantzig’s development of the simplex algorithm, Stigler was tasked to formulate a subsistence diet for the U.S. military. The goal was to minimize costs while delivering the Recommended Daily Allowances (RDAs) for a soldier [15]. This became known as the “Diet Problem.” Stigler’s initial findings were that, for $39.93 per annum ($751.81 in 2019 dollars), the U.S. military could feed a soldier while meeting the then-current nutritional standards. This annual subsistence diet consisted of five components: (1) 370 pounds of wheat flour, (2) 57 cans of evaporated milk, (3) 111 pounds of cabbage, (4) 23 pounds of spinach, and (5) 285 pounds of navy beans [15]. Stigler used a heuristic method to solve the Diet Problem. When this analysis was repeated using the simplex algorithm, Stigler’s finding was off by only 0.60% [18]. Of course, this solution meant
that a soldier would eat the same “meal” three times a day, every day. Thus, the Diet Problem was solved mathematically, but the solution validity was questionable. As Stigler himself stated, “No one recommends these diets for anyone, let alone everyone” [15]. Justifiably criticized as the “human dog biscuit” [16], Stigler’s Diet Problem solution propelled Stigler’s career, which culminated with him winning the Nobel Prize for Economics in 1982.

The Diet Problem has been revisited many times in the academic literature. The early reformulations, which were conducted when computing power was more limited than it is today, focused on modified constraints, such as updated RDA guidelines and food availability/pricing [17]. In some cases, different population subsets were assessed, such as age groups and genders [18]. As early as 1941—even before Stigler-Norwegian Nobel laureate Ragnar Frisch argued for the requirement for food to be palatable as well as nutritional when determining optimal human diets [19]. By 1959, studies began looking at food that, unlike Stigler’s solution, was consumed by the general public [20]. In 1970, Eckstein proposed that the term “Diet Problem” be used in reference to animals only, as palatability and variability were not a concern for animals. Eckstein noted that, when referencing humans, “Menu Problem” is a better descriptor [21].

As computing power increases, academic researchers can perform more complex linear programming calculations. This has led to not only adding meal palatability as a constraint [20] but also adding environmental sustainability [22].

According to Van Dooren, since 2000 there have been 52 academic papers published on the Diet Problem [23]. All 24 of the papers published between 2000 and 2009 used the traditional Diet Problem formulation of cost minimization constrained by nutritional requirements. Beginning in 2009, however, additional constraints began to emerge. For the period between 2009 and 2018, of the 28 publications focused on the Diet Problem, 10 utilized the traditional formulation, 12 added only environmental constraints, four added only palatability constraints, and two added both environmental and palatability constraints [24,25].

1.3. Family Meal Planning Under COVID-19 Scarcity Constraints

By mid-March 2020, the COVID-19 pandemic had caused a scarcity of numerous food products in U.S. supermarkets. Many normally-available products were missing from store shelves, including fresh bread, chicken, and meat (except frozen bulk ground beef), most fresh vegetables, nearly all canned vegetables and soups, and most “fast meals” (e.g., ramen noodles). By early April 2020, shelter-in-place orders had gone into effect in most states, inhibiting visits to supermarkets and trips to get “take-out” food from restaurants. Nearly all restaurants were closed for sit-down dining by early April. At the time of this writing, more than 36 million Americans had filed unemployment claims (22% of the workforce), with many more questioning their future job status and numerous others facing a reduced work schedule [26]. Driven by food unavailability, shelter-in-place orders, and constrained budgets, every U.S. family has been forced to re-evaluate its meal planning. The author viewed this as an opportunity to revisit the Diet Problem.

1.4. Author’s Contribution to the Literature

The traditional Diet Problem is a linear minimization problem subject to nutritional constraints. Over the last 20 years, increased computing power has enabled researchers to handle additional constraints. The goal of the author of this study is to demonstrate how to feed a family effectively during a pandemic.

This study minimizes family food costs subject to nutritional constraints, food availability, palatability of food combinations, and meal variation, and also restricts food shopping to one trip per month.

2. Methodology and Analysis

2.1. Problem Statement

As stated, the goal of this study is to use linear programming to determine the most economical way to feed a family effectively during a pandemic. The sub-goals are to (1) minimize cash outlays for food; (2) minimize potentially dangerous visits to the supermarket during a pandemic, specifically limiting shopping trips to one shopping event per month; (3) meet RDAs for a family as a whole and for each family member individually; (4) include only menu items that are generally available during the COVID-19 scarcity period; (5) develop food menus for individual meals (breakfast, lunch, dinner, and one snack every day); and (6) provide a diversity of meals, specifically meals that vary by day (i.e., the family does not eat the same breakfast, lunch, or dinner meal every day).

This formulation of the Diet Problem is examined in three scenarios, with each scenario adding additional constraints. Following Fletcher and colleagues [27], in the case in which not all constraints can be met, shadow costs are utilized to determine the best suboptimal solution.

The study assesses three scenarios and then systematically constructs a final solution. Discussed in more detail below, Scenario 1 is similar to Stigler’s approach; it uses the same menu for every meal every day, but it is based upon current RDAs and food generally available during the pandemic. This is referred to here as the “Human Dog Biscuit Scenario.” Scenario 2 adds the constraint of requiring the three traditional meals normally consumed in the United States (i.e., breakfast, lunch, dinner) together with foods that normally are eaten for those meals, but it still allows the unrealistic situation of consuming the same menu for each meal every day. This scenario is referred to here as the “3 Dog Biscuit Scenario.” The final scenario, Scenario 3, adds a meal-diversity constraint, requiring at least three different breakfasts, three different lunches, and three different dinners per week. This is referred to here as the “Realistic Scenario.”

2.2. The Data

Data on food availability during the pandemic were
gathered manually by visiting three supermarkets in the Denver, Colorado, metropolitan area on two different dates during the COVID-19 pandemic: Safeway, King Soopers, and a Target Superstore. Each store had significant systematic and relatively consistent inventory shortages. One trip to each store was made on a weekday, and one trip to each store was made on a weekend during the week of March 16, 2020. Only foods that were identified on all six supermarket visits were used in the study. “Exotic” foods were excluded and, where similar items were available, the least-expensive options were selected unless cheaper options were considerably less nutritious. All information was captured via cell phone photography for further analysis. Specific food data were saved via barcode scanning using an application called “Carb Manager” (version 6.3.5, Wombat Apps LLC). In the case where data were incomplete, the missing information was sourced from the specific food supplier or, in the case of commodities (e.g., fresh salmon), from the website nutritiondata.self.com. Table 1 lists the foods that were available in sufficient quantities at all six visits to the grocery stores.

| Item                  | Item Information                                      | Purchase Amount | Cost  | Serving Size |
|-----------------------|-------------------------------------------------------|-----------------|-------|--------------|
| Almonds               | Signature SELECT Almond Roasted & Salted              | 6 oz            | $2.50 | 1 oz         |
| Apple Juice           | Tree Top Honeycrisp 100% Apple Juice                  | 64 oz           | $1.99 | 8 oz         |
| Apple Sauce           | Kroger Classic Applesauce                             | 48 oz           | $1.99 | 4 oz         |
| Asparagus             | Fresh Asparagus                                       | 1 lb            | $2.99 | 5 spears     |
| Atlantic Salmon       | Fresh Farm Raised Atlantic Salmon Whole Fillet        | 4 oz            | $2.00 | 4 oz         |
| Bacon                 | Hormel Black Label Original Bacon                    | 16 oz           | $3.99 | 1 piece      |
| Bagel                 | Kroger 100% Whole Wheat Pre-Sliced Bagels             | 6 count         | $2.49 | 1 bagel      |
| Beef Jerky            | Original Jack Links Beef Jerky                        | 2.85 oz         | $3.99 | 0.5 oz       |
| Breaded Fish Fillets  | Gorton’s Crispy Buttered Fish Fillets                 | 10 count        | $6.99 | 2 fillets    |
| Burrito               | Tina’s Beef & Bean Burrito                            | 4 oz            | $0.40 | 1 burrito    |
| Butter                | Kroger Spreadable Butter with Canola Oil              | 15 oz           | $2.97 | 0.5 oz       |
| Butterfly Shrimp      | Kroger Crunchy Butterfly Shrimp                       | 32 oz           | $10.99| 3.2 oz       |
| Butternut Squash      | Butternut Squash                                      | 1 lb            | $1.29 | 1/2 cup      |
| Canned Baked Beans    | Bush’s Best Original Baked Beans                      | 28 oz           | $2.19 | 4.67 oz      |
| Canned Black Beans    | Kroger Black Beans                                    | 15.25 oz        | $0.89 | 4.33 oz      |
| Canned Corn           | Kroger Sweet Whole Kernel Golden Corn                 | 15.25 oz        | $0.69 | 4.33 oz      |
| Canned Green Beans    | Kroger Cut Green Beans                                | 14.5 oz         | $0.69 | 4.2 oz       |
| Canned Tuna           | Kroger Chunk Light Tuna in Oil                       | 5 oz            | $0.79 | 5 oz         |
| Cashews               | Signature SELECT Cashews Whole Roasted                | 6 oz            | $2.50 | 1 oz         |
| Cheese                | Kroger Swiss Cheese / Kroger Cheddar Cheese           | 16 oz           | $5.24 | 1 oz         |
| Chicken Pot Pie       | Banquet Chicken Pot Pie                               | 1 pie           | $0.89 | 1 pie        |
| Clam Chowder          | Kroger New England Style Clam Chowder                 | 18.8 oz         | $1.50 | 1 cup        |
| Cold Cereal           | Post Original Grape-Nuts                              | 20.5 oz         | $4.19 | 1 cup        |
| Cold Cereal           | Kroger Raisin Bran Cereal                             | 18.2 oz         | $2.29 | 1 cup        |
| Corn Tortilla Chips   | Signature SELECT Tortilla Chips White Corn            | 10.5 oz         | $1.50 | 1 oz         |
| Dry Pasta             | Kroger Thin Spaghetti Pasta                           | 16 oz           | $1.00 | 2 oz         |
| Eggs                  | Grade AA Large Eggs                                   | 12 count        | $1.59 | 1 egg        |
| English Muffins       | Kroger 100% Whole Wheat English Muffins               | 6 count         | $1.00 | 1 muffin     |
| Flour Tortillas       | Mission Tortillas Flour Soft Taco Super              | 10 count        | $1.99 | 1 tortilla   |
| Hamburger             | Kroger 91% Lean Frozen Ground Beef Burger             | 32 oz           | $9.99 | 4 oz         |
| Hash Browns           | Kroger Country Style Hash Browns                      | 30 oz           | $1.99 | 1 cup        |
| Hot Cereal            | Kroger Quick 1-Minute100% Whole Grain Oats            | 42 oz           | $4.39 | 1 cup        |
| Italian Sausage       | Signature SELECT Pork Sausage Roll Italian Style      | 16 oz           | $3.50 | 2 oz         |
| Jam                   | Kroger Strawberry Preserves                           | 32 oz           | $3.39 | 1 tbsp       |
| Orange Juice          | Signature SELECT/Farms Juice 100% Pure Orange        | 64 oz           | $2.50 | 8 oz         |
| Pancake Mix           | Krusteaz Pancake Mix Complete Blueberry              | 25.2 oz         | $2.50 | 1/2 cup      |
| Pasta Sauce           | Francesco Rinaldi Pasta Sauce Tomato & Basil (Jar)   | 24 oz           | $2.49 | 4.8 oz       |
| Peanut Butter         | Kroger Crunchy Peanut Butter                          | 16 oz           | $1.79 | 0.875 oz     |
| Peanuts               | Signature SELECT Peanuts Dry Roasted                  | 16 oz           | $2.59 | 1 oz         |
| Protein Bar           | CLIF Energy Bar Nuts & Seeds                          | 2.4 oz          | $1.29 | 1 bar        |
| Raspberries           | Fresh Raspberries                                    | 12 oz           | $4.99 | 1 cup        |
| Salsa                 | Pace Salsa Chunky                                    | 16 oz           | $2.49 | 2 oz         |
| Saltine Crackers      | Kroger Original Saltine Crackers                     | 16 oz           | $1.99 | 4 crackers   |
| Shrimp                | Kroger Shell-On Easy Peel Medium Raw Shrimp           | 16 oz           | $6.99 | 4 oz         |
| Smoked Salmon         | Alderwood Smoked Colorado Salmon                     | 4 oz            | $6.99 | 3 oz         |
| Soy Milk              | Silk Original Almondmilk                              | 64 oz           | $2.99 | 1 cup        |
| Strawberries          | Fresh Strawberries                                   | 1 lb            | $2.99 | 1 cup        |
| Syrup                 | Kroger Original Pancake Syrup                        | 24 oz           | $1.79 | 1 oz         |
| Tilapia               | Tilapia Fillet Fresh Farm Raised                     | 4 oz            | $1.00 | 4 oz         |
| Waffles               | Kroger Homestyle Waffles                             | 10 count        | $1.00 | 2 waffles    |
| Yogurt                | Lucerne Yogurt Low Fat Strawberry Banana             | 6 oz            | $0.50 | 1 container  |

Abbreviations: lb (pound), oz (ounce), tbsp (tablespoon).
The RDA data were sourced from Appendix F of the U.S. Food and Drug Administration’s publication, *A Food Labeling Guide: Guidance for Industry* [28]. However, not all of the RDAs and associated values must be published on the “Nutrition Facts” labelling mandated for all U.S. food items [28]. Because this information is not readily available to the consumer, only those RDAs required by labelling guidelines are used as constraints in this consumer-oriented study. Table 2 provides a list of the RDAs that are mandated by labelling requirements in the United States. The values are based upon a 2,000-calorie per day diet.

Table 2. Recommended Daily Allowances, For A 2,000-Calorie Diet

| Nutrient          | Lower Bound | Upper Bound |
|-------------------|-------------|-------------|
| Calories (kcal)   | 2,000       |             |
| Total Fat (g)     | 65          |             |
| Saturated Fat (g) | 20          |             |
| Cholesterol (mg)  | 300         |             |
| Sodium (mg)       | 2,400       |             |
| Potassium (mg)    | 3,500       | 300         |
| Total Carbohydrate (g) | 300 | |
| Dietary Fiber (g) | 25          |             |
| Protein (g)       | 50          |             |
| Vitamin A (IU)    | 5,000       | 250         |
| Vitamin C (mg)    | 60          | 65          |
| Calcium (mg)      | 1,000       |             |
| Iron (mg)         | 18          |             |

2.3. Model and Methods

The linear optimization model used in the present analyses is specified as follows.

Objective function: Minimise \( X \), subject to \( b \leq AX \leq c, DX \geq e \), \( X \geq 0 \) and integer.

In this set of equations, \( X \) is a function of the total cost of meal components, and in some problem formulations its units are required to be integers. \( A \) is a matrix containing the units of a nutrient per serving of a meal component, \( b \) is the vector of RDA lower bounds, and \( c \) is the vector of RDA upper bounds. \( D \) is a matrix containing food-meal combinations (e.g., bacon-breakfast), and \( e \) is the vector of meal constraints (e.g., the minimum number of different meals per week).

Linear optimization was performed using Excel 365 (version 2003.12624.20320) with the Solver Plugin. The simplex algorithm [12] was used, except in the case of non-linear constraints, in which case the Generalized Reduced Gradient non-linear algorithm was used instead [29].

2.4. Scenarios and Constraints

2.4.1. Scenario 1, the “Human Dog Biscuit Scenario”

As discussed, the “Human Dog Biscuit Scenario” is similar to Stigler’s approach—the same menu for every meal every day—but it is based upon current RDAs and foods generally available during the pandemic. There are three sub-scenarios, with constraints added in turn. In Scenario 1a, partial servings are allowed, meaning that the suggested “serving size” on the FDA-mandated product labels is not required to be followed. In Scenario 1b, partial servings are not allowed, so an integer constraint is imposed. In Scenario 1c, partial servings are not allowed, and no more than one serving of any food is allowed per meal. All RDA constraints shown in Table 2 are included in the analysis, as is each of the 51 foods listed in Table 1.

Table 3. Foods Categorized By Meal

| Component             | Breakfast | Lunch | Dinner | Snack | Fluid |
|-----------------------|-----------|-------|--------|-------|-------|
| Almonds               | Yes       |       |        |       |       |
| Apple Juice           | Yes       | Yes   | Yes    |       |       |
| Apple Sauce           | Yes       |       |        |       |       |
| Asparagus             | Yes       |       |        |       |       |
| Atlantic Salmon       | Yes       |       |        |       |       |
| Bacon                 | Yes       |       |        |       |       |
| Bagel                 | Yes       | Yes   |        |       |       |
| Beef Jerky            | Yes       |       |        |       |       |
| Breaded Fish Fillets  | Yes       |       |        |       |       |
| Burrito               | Yes       |       |        |       |       |
| Butter                | Yes       | Yes   | Yes    |       |       |
| Butterfly Shrimp      | Yes       |       |        |       |       |
| Butternut Squash      | Yes       |       |        |       |       |
| Canned Baked Beans    | Yes       |       |        |       |       |
| Canned Black Beans    | Yes       |       | Yes    |       |       |
| Canned Corn           | Yes       |       | Yes    |       |       |
| Green Beans           | Yes       | Yes   | Yes    |       |       |
| Canned Tuna           | Yes       |       |        |       |       |
| Cashews               | Yes       |       |        |       |       |
| Cheese                | Yes       | Yes   | Yes    | Yes   |       |
| Chicken Pot Pie       | Yes       |       |        |       |       |
| Clam Chowder          | Yes       |       |        |       |       |
| Cold Cereal, Grape-Nuts | Yes   |       |        |       |       |
| Cold Cereal, Raisin Bran | Yes |       |        |       |       |
| Corn Tortilla Chips   | Yes       | Yes   | Yes    |       |       |
| Dry Pasta             | Yes       |       |        |       |       |
| Eggs                  | Yes       |       |        |       |       |
| English Muffins       | Yes       |       |        |       |       |
| Flour Tortillas       | Yes       | Yes   |        |       |       |
| Hamburger             | Yes       |       |        |       |       |
| Hash Browns           | Yes       |       |        |       |       |
| Hot Cereal            | Yes       |       |        |       |       |
| Italian Sausage       | Yes       | Yes   | Yes    |       |       |
| Jam                   | Yes       |       |        |       |       |
| Orange Juice          | Yes       | Yes   | Yes    |       |       |
| Pancake Mix           | Yes       |       |        |       |       |
| Pasta Sauce           | Yes       | Yes   |        |       |       |
| Peanut Butter         | Yes       |       |        |       |       |
| Peanuts               | Yes       |       |        |       |       |
| Protein Bar           | Yes       |       |        |       |       |
| Raspberries           | Yes       | Yes   | Yes    |       |       |
| Salsa                 | Yes       | Yes   | Yes    |       |       |
| Saltine Crackers      | Yes       |       | Yes    |       |       |
| Shrimp                | Yes       | Yes   | Yes    |       |       |
| Smoked Salmon         | Yes       |       |        |       |       |
| Soy Milk              | Yes       | Yes   | Yes    | Yes   |       |
| Strawberries          | Yes       |       |        | Yes   |       |
| Syrup                 | Yes       |       |        |       |       |
| Tilapia               | Yes       |       |        |       |       |
| Waffles               | Yes       |       |        |       |       |
| Yogurt                | Yes       | Yes   |        |       |       |
2.4.2. Scenario 2, the “3 Dog Biscuit Scenario”

Scenario 2 has the constraints of the current RDAs and food generally available during the pandemic and adds a constraint requiring the three daily meals normally consumed in the United States (i.e., breakfast, lunch, and dinner) as well as an additional constraint requiring that only foods that are traditionally consumed in those meals are available for those meals. To determine which foods traditionally were consumed with each meal, the author followed Leung et al., who determined food-combination palatability based upon modern recipes [30]. Each of the 51 foods is characterized as breakfast food, lunch food, dinner food, snack food, or drink/fluid. Foods can be in more than one category, but only foods that are characterized for a specific meal are included in the scenario for that specific meal type (i.e., bacon is only characterized as breakfast food, so it is not included in the lunch or dinner sub-scenarios). This categorization results in 19 breakfast foods, 24 lunch foods, 19 dinner foods, 14 snack foods, and three drinks. The food-meal type categories determined for this study are shown in Table 3. Additionally, this scenario still allows the unrealistic situation of consuming the same menu for each meal every day.

Scenario 2 has several sub-scenarios for each meal type. The breakfast scenarios are described here, with the lunch and dinner scenarios being identical except for the included foods, as described in Table 3. Similar to Scenario 1, in Scenario Breakfast 2a (B2a) partial servings of the meal component are allowed. In Scenario Breakfast 2b (B2b), however, partial servings are not allowed. In addition to the integer constraint imposed in B2b, Scenario Breakfast 2c (B2c) requires that no more than one serving of any food is allowed per meal. Following Parlesak and colleagues’ work on “food baskets” [31], and unlike Scenario 1, Scenario Breakfast 2d (B2d) adds to the B2c constraints one that this study calls “optimized meals.” Optimized meals require that certain foods be consumed together (e.g., pancakes require syrup; dry cereal requires milk). The lunch scenarios are denoted as Scenarios L2a through L2d, and the dinner scenarios are Scenarios D2a through D2d.

2.4.3. Scenario 3, the “Realistic Scenario”

For Scenario 3—the most realistic of all the scenarios in this analysis—the author followed Petot et al. and determined menus for seven different commonly eaten meals for each meal type (breakfast, lunch, and dinner), based upon the 51 foods available, and identified 11 snacks and three drinks [32]. The breakdown is shown in Table 4.

Scenario 3 includes Scenario 2 constraints of individual meals (breakfast, lunch, and dinner) and adds a snack each day. Additionally, Scenario 3c includes a meal-diversity constraint that requires at least three different breakfasts, three different lunches, and three different dinners per week. Similar to the other scenarios, there are several sub-scenarios in Scenario 3. Scenario 3a—in addition to the RDA constraints and pandemic-driven meal-availability constraints—requires three meals of any type, a snack, and three drinks per day for 28 days, but partial meals are not allowed. Scenario 3b is very similar to Scenario 3a, except

| Table 4. Meal Descriptions |
|----------------------------|
| Meal Number | Meal |
| Breakfast 1 | Oatmeal with Soy Milk and English Muffin |
| Breakfast 2 | Grape-Nuts Cereal with Soy Milk and English Muffin |
| Breakfast 3 | Eggs and Bacon, with Hash Browns and English Muffin |
| Breakfast 4 | Grape-Nuts Cereal with Soy Milk and English Muffin |
| Breakfast 5 | Waffles with Syrup and Strawberries, with Hash Browns |
| Breakfast 6 | Pancakes with Syrup and Raspberries, with Hash Browns |
| Breakfast 7 | Sausage and Cheese Omelette, with Hash Browns and English Muffin |
| Lunch 1 | Tuna on Bagel, with Corn |
| Lunch 2 | Smoked Salmon, Clam Chowder with Saltines, and Green Beans |
| Lunch 3 | Sausage and Cheese Omelette, with Hash Browns and English Muffin |
| Lunch 4 | Chicken Pot Pie and Green Beans |
| Lunch 5 | Nachos with Beef, Bean, Cheese, and Salsa |
| Lunch 6 | Breaded Fish Fillets and Baked Beans |
| Lunch 7 | Shrimp and Cheese Burrito, with Chips and Salsa and Black Beans |
| Dinner 1 | Butterfly Shrimp, with Corn |
| Dinner 2 | Burrito with Beef, Beans, Cheese, with Chips and Salsa |
| Dinner 3 | Burrito with Shrimp, Beans, Cheese, with Chips and Salsa |
| Dinner 4 | Salmon with Butternut Squash |
| Dinner 5 | Tilapia with Asparagus |
| Dinner 6 | Pasta, and Tomato Sauce with Beef |
| Dinner 7 | Pasta, and Tomato Sauce with Sausage |
| Snack 1 | Chips and Salsa |
| Snack 2 | Beef Jerky |
| Snack 3 | Apple Sauce |
| Snack 4 | Protein Bar |
| Snack 5 | Strawberries |
| Snack 6 | Raspberries |
| Snack 7 | Yogurt |
| Snack 8 | Saltines with Peanut Butter and Jam |
| Snack 9 | Almonds |
| Snack 10 | Peanuts |
| Drink 1 | Soy Milk |
| Drink 2 | Apple Juice |
| Drink 3 | Orange Juice |

2.5. Summary of Scenarios

Table 5 provides a summary of all constraints in addition to the RDA and food-availability constraints for all 10 scenarios.
Table 5. Summary Of Scenarios

| Scenario | Constraints in Addition to RDAs and Food Availability |
|----------|-------------------------------------------------------|
|          | No Partial Servings/ Meals | No More Than One Serving Per Meal | Separate Breakfast, Lunch, and Dinner | Optimized Meals | Meal Diversity |
| 1a       |                         |                                 |                                    |               |               |
| 1b       | Yes                     |                                 |                                    |               |               |
| 1c       | Yes                     | Yes                             |                                    |               |               |
| 2Ba, 2La, 2Da |                         |                                 |                                    |               |               |
| 2Bb, 2Lb, 2Db | Yes                     |                                 |                                    |               |               |
| 2Bc, 2Lc, 2Dc | Yes                     | Yes                             |                                    |               |               |
| 2Bd, 2Ld, 2Dd | Yes                     | Yes                             |                                    | Yes           | Yes           |
| 3a       | Yes                     | Yes                             | Yes                                 | Yes           | Yes           |
| 3b       | Yes                     |                                 |                                    |               |               |
| 3c       | Yes                     | Yes                             |                                    | Yes           | Yes           |

3. Results

3.1. Results Introduction

For the purpose of this study, a theoretical family of four with the following attributes was considered: (1) a moderately active man, age 41, consuming the recommended 2,600 calories per day; (2) an active woman, age 35, consuming the recommended 2,200 calories per day; (3) a sedentary male child, age 12, consuming the recommended 1,800 calories per day; and (4) a moderately active female child, age 6, consuming 1,400 calories per day. The female parent is not pregnant and is not planning to become pregnant in the foreseeable future. No family members identified significant health issues, and no family members have any allergies or self-imposed eating restrictions (e.g., no family member is a vegetarian). This family needs to consume the nutrients associated with 8,000 calories per day total. The goal was to feed the family-maintaining all RDAs (as defined)-for one month (28 days) with only one visit to the supermarket (food items either must last 28 days or can be frozen without significant impairment in quality).

3.2. Scenario 1 Results

As discussed, Scenario 1 is the “Human Dog Biscuit Scenario”; there is only one menu of food for each day. The results of Scenario 1 are shown in Table 6.

Table 6. Results For Scenario 1

Panel A. Scenario 1a: Same Menu Every Meal Every Day for a 2,000-Calorie Diet

| Menu            | Servings | Nutrient   | Recommended Maximum | Recommended Minimum |
|-----------------|----------|------------|----------------------|--------------------|
| Waffles         | 0.157    | Calories   | 100.0%               |                    |
| Canned Black Beans | 2.687  | Total Fat  | 100.0%               |                    |
| Dry Pasta       | 3.814    | Saturated Fat | 44.9%              |                    |
| Peanut Butter   | 3.456    | Cholesterol | 0.3%                |                    |
| Butternut Squash| 0.302    | Sodium     | 73.6%                |                    |
| Orange Juice    | 0.703    | Potassium  | 100.0%               |                    |
| Soy Milk        | 1.519    | Total Carbohydrates | 94.5%          |                    |

Panel B. Scenario 1b: Same Menu Every Meal Every Day with Whole Servings

| Menu            | Servings | Nutrient   | Recommended Maximum | Recommended Minimum |
|-----------------|----------|------------|----------------------|--------------------|
| Waffles         | 1.000    | Calories   | 102.0%               |                    |
| English Muffins | 1.000    | Total Fat  | 87.8%                |                    |
| Hot Cereal      | 5.000    | Saturated Fat | 30.5%              |                    |
| Peanut Butter   | 1.000    | Cholesterol | 1.7%                |                    |
| Canned Black Beans | 3.000 | Sodium     | 94.4%                |                    |
| Peanuts         | 1.000    | Potassium  | 101.2%               |                    |
| Orange Juice    | 1.000    | Tot. Carbohydrates | 99.7%          |                    |
| Soy Milk        | 1.000    | Dietary Fiber | 196.8%            |                    |

Cost per Day $2.55

Cost per Day $2.84
very few Americans meet 100% of the RDAs on any day, much less every day [33]. The author, therefore, deemed these slight deviations from a single RDA to be acceptable. Scenario 2Bd (Panel D) is a very palatable breakfast menu, as determined by the meal being available in nearly every American breakfast restaurant [34].

### Table 7. Results For Scenario 2 Breakfast

| Menu                  | Servings | Nutrient       | Recommended Maximum | Recommended Minimum |
|-----------------------|----------|----------------|---------------------|---------------------|
| Raisin Bran           | 1.000    | Calories       | 101.0%              |                     |
| Hot Cereal            | 1.000    | Total Fat      | 95.9%               |                     |
| Soy Milk              | 1.000    | Saturated Fat  | 59.5%               |                     |
| Hash Browns           | 1.000    | Cholesterol    | 20.0%               |                     |
| Orange Juice          | 1.000    | Sodium         | 96.8%               |                     |
| Bagel                 | 1.000    | Potassium      |                     | 101.5%              |
| Peanut Butter         | 1.000    | Total Carbohydrate | 99.0%       |                     |
| Canned Black Beans    | 1.000    | Dietary Fiber  | 150.8%              |                     |
| Peanuts               | 1.000    | Protein        | 155.2%              |                     |
| Sultine Crackers      | 1.000    | Vitamin A      | 310.9%              |                     |
| Italian Sausage       | 1.000    | Vitamin C      | 175.8%              |                     |
| Butternut Squash      | 1.000    | Calcium        | 102.5%              |                     |
| Dry Pasta             | 1.000    | Iron           | 106.7%              |                     |
| English Muffins       | 1.000    |                |                     |                     |

For all three sub-scenarios, the constraints are met, except for the calorie constraint for 1b (Table 6, Panel B) and 1c (Table 6, Panel C), which are within 2.0% of holding. As constraints are imposed, costs increase from an average of $2.55 per family member per day for Scenario 1a to an average of $3.00 per family member per day for Scenario 2c. Scenario 1c begins to become palatable; but, as noted, it is unlikely that any family would choose this diet for more than one day, much less for an entire month. This scenario, however, can serve as the “base case” for comparison with the remaining scenarios.

### 3.3. Scenario 2 Results

As mentioned, Scenario 2 is the “3 Dog Biscuit Scenario”; namely, a distinct breakfast, a distinct lunch, and a distinct dinner but the same breakfast, lunch, and dinner every day. Because each meal is a unique subproblem of the scenario, each is discussed in turn below. Additionally, the three meals together are based upon a 2,000-calorie diet, with 40% of the calories allocated to dinner and 30% each to breakfast and lunch.

#### 3.3.1. Scenario 2, Breakfast

All Scenario 2 breakfast foods (Scenarios 2Ba through 2Bd) are shown in Table 7.

As shown in Table 7, the breakfast meal becomes much more expensive as constraints are added. There is a 215.2% increase from Scenario 2Ba to Scenario 2Bd (an average of $1.05 to $3.31 per family member per day), driven predominately by palatability constraints, even given that all RDA constraints are not met in Scenarios 2Bc and 2Bd, with the total fat constraint being relaxed in Scenario 2Bc (106.2%), and with the total carbohydrate constraint being relaxed in Scenario 2Bd (120.5%). Without relaxing constraints, there are no solutions to the problems identified in these scenarios. The solutions shown are not the only possible solutions; however, they were the solutions that allowed the minimum deviation from a single constraint to solve the problem and minimize that deviation in percentage terms. As discussed by Maillot and colleagues, very few Americans meet 100% of the RDAs on any day, much less every day [33]. The author, therefore, deemed these slight deviations from a single RDA to be acceptable. Scenario 2Bd (Panel D) is a very palatable breakfast menu, as determined by the meal being available in nearly every American breakfast restaurant [34].

### Table 7. Results For Scenario 2 Breakfast

| Panel A. Scenario 2Ba: Same Breakfast Menu Every Day, Partial Servings Allowed, for a 600-Calorie Meal | Cost per Day | $1.05 |
|------------------------------------------------------------------------------------------------|-------------|-------|
| Menu                  | Servings | Recommended Daily Allowances |             |       |
| Eggs                  | 0.433    | All constraints met          |             |       |
| Hot Cereal            | 1.857    |                             |             |       |
| Grape-Nuts            | 0.051    |                             |             |       |
| Soy Milk              | 0.634    |                             |             |       |
| Hash Browns           | 1.534    |                             |             |       |
| Butter                | 1.084    |                             |             |       |
| Orange Juice          | 0.154    |                             |             |       |

| Panel B. Scenario 2Bb: Same Breakfast Menu Every Day, Whole Servings Only, for a 600-Calorie Meal | Cost per Day | $1.55 |
|-------------------------------------------------------------------------------------------------|-------------|-------|
| Menu                  | Servings | Recommended Daily Allowances |             |       |
| Grape-Nuts            | 1.000    | All constraints met          |             |       |
| Soy Milk              | 2.000    |                             |             |       |
| Butter                | 1.000    |                             |             |       |
| Orange Juice          | 1.000    |                             |             |       |

| Panel C. Scenario 2Bc: Same Breakfast Menu Every Day, Whole Servings Only, No More Than One Serving per Meal, for a 600-Calorie Meal | Cost per Day | $1.86 |
|-------------------------------------------------------------------------------------------------|-------------|-------|
| Menu                  | Servings | Recommended Daily Allowances |             |       |
| Waffles               | 1.000    | Total Fat = 106.2%           |             |       |
| Butter                | 1.000    | All other constraints met    |             |       |
| Strawberries          | 1.000    |                             |             |       |
| Jam                   | 1.000    |                             |             |       |
| Soy Milk              | 1.000    |                             |             |       |
| Orange Juice          | 1.000    |                             |             |       |

| Panel D. Scenario 2Bd: Same Breakfast Menu Every Day, Whole Servings Only, Optimized Meals, for a 600-Calorie Meal | Cost per Day | $3.31 |
|-------------------------------------------------------------------------------------------------|-------------|-------|
| Menu                  | Servings | Recommended Daily Allowances |             |       |
| Waffles               | 1.000    | Total Carbohydrate = 120.5%  |             |       |
| Syrup                 | 1.000    | All other constraints met    |             |       |
| Raspberries           | 1.000    |                             |             |       |
| Strawberries          | 1.000    |                             |             |       |
| Hash Browns           | 1.000    |                             |             |       |
| Soy Milk              | 1.000    |                             |             |       |
### 3.3.2. Scenario 2, Lunch

All Scenario 2 lunch menus (Scenarios 2La through 2Ld) are shown in Table 8.

| Table 8. Results For Scenario 2 Lunch |
|--------------------------------------|
| **Panel A. Scenario 2La: Same Lunch Menu Every Day, Partial Servings Allowed, for a 600-Calorie Meal** |
| Cost per Day | $1.80 |
| Menu | Servings | Recommended Daily Allowances |
| Hamburger | 0.054 | All constraints met |
| Canned Corn | 0.943 |  |
| Corn Tortilla Chips | 0.156 |  |
| Salsa | 0.555 |  |
| Apple Juice | 1.424 |  |
| Soy Milk | 2.867 |  |

| **Panel B. Scenario 2Lb: Same Lunch Menu Every Day, Whole Servings Only, for a 600-Calorie Meal** |
| Cost per Day | $2.74 |
| Menu | Servings | Recommended Daily Allowances |
| Hamburger | 1.000 | Total Fat = 106.7% |
| Pasta Sauce | 1.000 | All other constraints met |
| Apple Juice | 1.000 |  |
| Soy Milk | 2.000 |  |

| **Panel C. Scenario 2Lc: Same Lunch Menu Every Day, Whole Servings Only, No More Than One Serving per Meal, for a 600-Calorie Meal** |
| Cost per Day | $1.74 |
| Menu | Servings | Recommended Daily Allowances |
| Canned Corn | 1.000 | Total Fat = 115.4% |
| Pasta Sauce | 1.000 | Sodium = 177.1% |
| Butter | 1.000 | All other constraints met |
| Corn Tortilla Chips | 1.000 |  |
| Apple Juice | 1.000 |  |
| Soy Milk | 2.000 |  |

| **Panel D. Scenario 2Ld: Same Lunch Menu Every Day, Whole Servings Only, Optimized Meals, for a 600-Calorie Meal** |
| Cost per Day | $2.74 |
| Menu | Servings | Recommended Daily Allowances |
| Hamburger | 1.000 | Total Fat = 106.7% |
| Pasta Sauce | 1.000 | All other constraints met |
| Apple Juice | 1.000 |  |
| Soy Milk | 2.000 |  |

As in Scenario 2B, Scenario 2L exhibits increasing costs as constraints are added. Note, however, that Scenario 2Le costs decrease from those of Scenario 2Lb because not all constraints hold. Specifically, in Scenario 2Lc (Table 8, Panel C), total fat exceeds the RDA by 15.4% and sodium exceeds the RDA by 77.1%. Given these facts—especially the sodium amount—the author determined that the optimal constraint to be relaxed was not a nutrient constraint but rather the constraint that limited meals to single-component servings. This resulted in the solution to Scenario 2Ld (Table 8, Panel D) being a double serving of soy milk with lunch. The author deemed this to be palatable because it results in a 16-ounce serving of soy milk, which is 69.6% of the average amount of a drink consumed per meal based upon a serving size study by Bryant and Dundes [35].

### 3.3.3. Scenario 2, Dinner

All Scenario 2 dinner menus (Scenarios 2Da through 2Dd) are shown in Table 9 below.

| Table 9. Results For Scenario 2 Dinner |
|---------------------------------------|
| **Panel A. Scenario 2Da: Same Dinner Menu Every Day, Partial Servings Allowed, for an 800-Calorie Meal** |
| Cost per Day | $1.39 |
| Menu | Servings | Recommended Daily Allowances |
| Italian Sausage | 0.043 |  |
| Butternut Squash | 0.614 |  |
| Salsa | 0.375 |  |
| Canned Black Beans | 1.136 |  |
| Canned Corn | 0.547 |  |
| Dry Pasta | 1.683 |  |
| Butter | 2.195 |  |
| Soy Milk | 0.586 |  |

| **Panel B. Scenario 2Db: Same Dinner Menu Every Day, Partial Servings Allowed, for an 800-Calorie Meal** |
| Cost per Day | $1.81 |
| Menu | Servings | Recommended Daily Allowances |
| Butternut Squash | 1.000 | Calories = 101.3% |
| Canned Black Beans | 1.000 |  |
| Corn Tortilla Chips | 1.000 |  |
| Dry Pasta | 1.000 |  |
| Soy Milk | 2.000 |  |

| **Panel C. Scenario 2Dc: Same Dinner Menu Every Day, Partial Servings Allowed, for an 800-Calorie Meal** |
| Cost per Day | $2.43 |
| Menu | Servings | Recommended Daily Allowances |
| Tilapia | 1.000 | Calories = 106.3% |
| Butternut Squash | 1.000 | All other constraints met |
| Canned Black Beans | 1.000 |  |
| Corn Tortilla Chips | 1.000 |  |
| Dry Pasta | 1.000 |  |
| Soy Milk | 1.000 |  |

| **Panel D. Scenario 2Dd: Same Dinner Menu Every Day, Partial Servings Allowed, for an 800-Calorie Meal** |
| Cost per Day | $2.77 |
| Menu | Servings | Recommended Daily Allowances |
| Tilapia | 1.000 | Calories = 106.3% |
| Flour Tortillas | 1.000 | Sodium = 117.9% |
| Corn Tortilla Chips | 1.000 | All other constraints met |
| Butternut Squash | 1.000 |  |
| Pasta Sauce | 1.000 |  |
| Dry Pasta | 1.000 |  |
| Soy Milk | 1.000 |  |

As expected, the cost increases as each constraint is added in Scenario 2D, concluding with a total average cost of $2.77 per family member per day for the optimized meal (Table 9, Panel D). The calorie constraint is within 6.3% of the goal, which is a function of integer-serving requirements, but the sodium RDA is exceeded by 17.9%. As in Scenarios 2Bd and 2Ld, no solution can be found where all constraints hold.

### 3.3.4. Scenario 2 Summary

When considering the final sub-scenario of each meal type in Scenario 2 (Panel D of Table 7, Table 8, and
Table 9), the total average cost per family member per day is $8.82, even though not all constraints hold in every case. This is substantially more expensive than Scenario 1, where the most palatable option, Scenario 1C (Table 6, Panel C), costs an average of $3.00 per family member per day. The cost of meal diversity, in this case, a breakfast of breakfast-specific foods, a lunch of lunch-specific foods, and a dinner of dinner-specific foods versus a single menu for every meal every day, comes at a significant cost increase, specifically a 194.0% premium.

3.4. Scenario 3 Results

As discussed, Scenario 3 is the “realistic scenario,” as a series of breakfast meals, a series of lunch meals, and a series of dinner meals were determined based upon available foods and common tastes. Scenario 3a allows partial meals, but Scenario 3b does not. Scenario 3c does not allow partial meals and requires meal diversity (i.e., at least three different breakfasts, three different lunches, and three different dinners per week). The results of Scenario 3 are shown in Table 10.

| Table 10. Results For Scenario 3 |
|-----------------------------------|
| Panel A. Scenario 3a: Partial Meals Allowed, Based Upon a 2,000-Calorie Diet |
| Cost per Day | $4.14 |
| Meal | Meal Description | Meals per Month | Recommended Daily Allowances |
| Breakfast 1 Oatmeal with Soy Milk, and English Muffin | 41.320 | Calories = 103.1% |
| Breakfast 2 Grape-Nuts with Soy Milk, and English Muffin | 9.262 |
| Dinner 7 Pasta, and Tomato Sauce with Sausage | 33.417 |
| Snack 3 Apple Sauce | 16.931 |
| Snack 10 Peanuts | 11.069 |
| Drink 1 Soy Milk | 24.501 |
| Drink 2 Apple Juice | 20.958 |
| Drink 3 Orange Juice | 38.541 |
| Panel B. Scenario 3b: Partial Meals Not Allowed, Based Upon a 2,000-Calorie Diet |
| Cost per Day | $4.15 |
| Meal | Meal Description | Meals per Month | Recommended Daily Allowances |
| Breakfast 1 Oatmeal with Soy Milk, and English Muffin | 41.000 | Calories = 102.8% |
| Breakfast 2 Grape-Nuts with Soy Milk and English Muffin | 10.000 |
| Lunch 4 Chicken Pot Pie and Green Beans | 2.000 |
| Dinner 7 Pasta, and Tomato Sauce with Sausage | 31.000 |
| Snack 3 Apple Sauce | 16.000 |
| Snack 10 Peanuts | 12.000 |
| Drink 1 Soy Milk | 21.000 |
| Drink 2 Apple Juice | 16.000 |
| Drink 3 Orange Juice | 47.000 |
| Panel C. Scenario 3c: Partial Meals Not Allowed and Meal Variety Required, Based Upon a 2,000-Calorie Diet |
| Cost per Day | $5.33 |
| Meal | Meal Description | Meals per Month | Recommended Daily Allowances |
| Breakfast 1 Oatmeal with Soy Milk and English Muffin | 4.000 | Total Fat = 118.4% |
| Breakfast 2 Grape-Nuts with Soy Milk and English Muffin | 4.000 | Saturated Fat = 111.6% |
| Breakfast 3 Eggs, Bacon, Hash Browns, and English Muffin | 4.000 | Sodium = 133.3% |
| Breakfast 4 Grape-Nuts with Soy Milk and English Muffin | 4.000 | Potassium = 84.6% |
| Breakfast 7 Sausage and Cheese Omelette, Hash Browns, and English Muffin | 12.000 | Vitamin A = 62.4% |
| Lunch 1 Tuna on Bagel, with Corn | 8.000 | Iron = 96.8% |
| Lunch 4 Chicken Pot Pie and Green Beans | 8.000 |
| Lunch 5 Nachos with Beef, Bean, Cheese, and Salsa | 4.000 |
| Lunch 6 Breaded Fish Fillets and Baked Beans | 8.000 |
| Dinner 1 Butterfly Shrimp and Corn | 12.000 |
| Dinner 2 Beef, Beans, and Cheese Burrito, and Chips and Salsa | 4.000 |
| Dinner 7 Pasta, and Tomato Sauce with Sausage | 12.000 |
| Snack 1 Chips and Salsa | 24.000 |
| Snack 3 Apple Sauce | 4.000 |
| Drink 1 Soy Milk | 24.000 |
| Drink 2 Apple Juice | 28.000 |
| Drink 3 Orange Juice | 32.000 |
As expected, the addition of constraints increases costs from Scenario 3a to Scenario 3b to Scenario 3c (Table 10, Panels A, B, and C, respectively). None of these scenarios can be solved without relaxing at least one constraint, and Scenario 3c requires the relaxation of several constraints, given its complexity.

In addition to the relaxed constraints shown explicitly in Table 10, there is another significant relaxation of the RDA constraint for all sub-scenarios in Scenario 3: all RDAs are an average of a 28-day month. In all prior scenarios, the RDAs are a true daily average. This is a significant relaxation of constraints, but the author deemed it to be realistic for the meal planning of an average U.S. family. For this reason, the overall cost of Scenario 3c—the most expensive sub-scenario in Scenario 3—is an average of $5.33 per family member per day (Table 10, Panel C), considerably less than the most expensive sub-scenarios in Scenario 2 (at $8.82) (see Table 7, Panel D; Table 8; and Table 9).

Because the number of meals by type per week is a non-linear constraint, a different optimization method was required to solve Scenario 3c (Table 10, Panel C)—the Generalized Reduced Gradient non-linear algorithm (GRG Method) was employed [29].

### 3.5. Scenario Comparison

The author regards Scenario 3c (Table 10, Panel C) as the most realistic scenario for actual family meal planning, given that all of the other scenarios in this study are not practical ways for a family to eat over an extended period, such as a month. Because of the relaxation of multiple constraints, however, the cost per day of this scenario for a 2,000-calorie diet is less than that of Scenario 2, but it is much greater than all sub-scenarios in Scenario 1, as shown in Figure 1.

Scenario 1 increases in cost with each additional constraint. Scenario 2 is very expensive because each meal is optimized and very few constraints are violated (i.e., more diversity than Scenario 1). Scenario 3 is less expensive than Scenario 2 because six RDAs are not met (although the delta is minimized in each case), but the more impactful constraint is that the RDA levels are optimized on average for the month, not for each day.

---

**Table 11. Scenario 3c Grocery List**

| Item                            | Size       | Containers Required | Cost Per Container | Total Cost |
|---------------------------------|------------|---------------------|--------------------|------------|
| Bacon, Hormel Black Label       | 16 oz      | 2.00                | $3.99              | $7.98      |
| Beef, Ground, 91% Lean, Frozen, Kroger | 2 lbs | 4.00                | $9.99              | $39.96     |
| Chicken Pot Pie, Banquet        | 7 oz       | 32.00               | $0.89              | $28.48     |
| Fish Fillets, Gorton’s Crispy Battered | 10 count | 7.00                | $6.99              | $48.93     |
| Pork Sausage, Signature SELECT  | 16 oz      | 12.00               | $3.50              | $42.00     |
| Shrimp, Butterfly, Crunchy, Kroger | 32 oz | 5.00                | $10.99             | $54.95     |
| Tuna, in Oil, Kroger Chunk Light | 5 oz | 32.00               | $0.79              | $25.28     |
| Eggs, Grade AA Large, Kroger    | 12 count   | 6.00                | $1.59              | $9.54      |
| Cheese, Swiss/Cheddar Kroger    | 16 oz      | 6.00                | $5.24              | $31.44     |
| Butter with Canola Oil, Spreadable, Kroger | 15 oz | 6.00                | $2.97              | $17.82     |
| Bagels, Whole Wheat Pre-Sliced, Kroger | 6 count | 6.00                | $2.49              | $14.94     |
| English Muffins, Kroger 100% Whole Wheat | 6 count | 19.00               | $1.00              | $19.00     |
| Tortillas, Flour, Mission Soft Taco Super | 10 count | 2.00                | $1.99              | $3.98      |
| Silk Original Almond milk       | 1/2 gallon | 18.00               | $2.99              | $53.82     |
| Orange Juice, Signature SELECT100% Pure | 64 oz | 16.00               | $2.50              | $40.00     |
| Apple Juice, Tree Top Honeycrisp 100% | 64 oz | 14.00               | $1.99              | $27.86     |
| Applesauce, Kroger Classic      | 48 oz      | 2.00                | $1.99              | $3.98      |

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*Figure 1. Scenario comparison: average cost per day for 2,000-calorie diet*
3.6. Family Meal Planning under COVID-19 Scarcity

As discussed, the goal of this study is to demonstrate that a family can be effectively fed a palatable and diversified diet during a pandemic while minimizing costs and trips to the supermarket and meeting minimum RDAs to the extent possible. Because our foods are bought per container and in bulk, there will be some “leftovers” at the end of the 28-day month. Using the results of Scenario 3c-the most realistic scenario for actual family meal planning-the hypothetical family of four would make one grocery store trip at the beginning of the month and would purchase all of the items listed in Table 11, at a total cost of $631.52.

After a full month of meals, there are some leftovers for our hypothetical family of four, specifically because the constraints of Scenario 3c were to require full servings, but the food is purchased per unit or per container. The total value of the leftovers is $34.56.

4. Conclusions

4.1. Summary

The Stigler Diet Problem was revisited under the constraints of the current-day COVID-19 pandemic. The author identified 51 readily available meal ingredients that could be stored for a minimum of a month (frozen or otherwise). Several scenarios were analyzed, with the goals of minimizing costs, meeting minimum RDAs, and maximizing edibility/diversity. An additional goal was requiring only one shopping event per month, thus minimizing exposure to COVID-19. An acceptable and diversified one-month meal plan that minimized costs and minimized the relaxation of average monthly minimum RDAs was identified for a hypothetical family of four. The total monthly cost of this meal plan is $631.52. Certain RDAs, however, were not met on average over the course of the month due to the complexity of the imposed constraints. Specifically, the family would exceed total fat allowances by about 18.4%, total saturated fat RDA by 11.6%, and the sodium RDA by 33.3%; however, most families in the United States regularly exceed many of the maximum RDAs [33]. Certain minimum RDAs are not met by this proposed diet, specifically potassium (84.6% of the RDA) and Vitamin A (62.4% of the RDA). These nutrients are readily available as dietary supplements at U.S. supermarkets. It costs an estimated additional $0.36 per day ($9.99 per month) for supplements for the family to meet the RDAs of these nutrients, bringing the final cost to $641.51.

4.2. Contribution

This study serves dual purposes. First, it highlights linear optimization, a method not normally considered by business researchers. More importantly, the results here can be used as a blueprint to demonstrate to families that healthy menus can be purchased very inexpensively from supermarkets during pandemic-related scarcities, and visits to the supermarket can also be limited to one per month to reduce dangerous exposure. Although the available foods in this study were identified in the Denver, Colorado, metropolitan area at the height of the pandemic, it is likely that the global supply chains of the major grocery store chains assessed in this study would be similar across the country, albeit not without regional or super-regional differences. Additionally, it is unlikely that a family would follow this exact blueprint for pandemic meal planning. Even in the case where the identified foods are not available in different areas of the country—or if family taste differences existed—the U.S. food labeling guidelines are such that it would not be time-consuming or challenging to substitute foods in the grocery list in Table 11 with other foods with similar nutrient values.

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| Item                                      | Size | Containers Required | Cost Per Container | Total Cost |
|-------------------------------------------|------|---------------------|--------------------|------------|
| Strawberry Preserves, Kroger              | 32 oz| 3.00                | $3.39              | $10.17     |
| Baked Beans, Bush’s Best Original         | 28 oz| 6.00                | $2.19              | $13.14     |
| Black Beans, Kroger                       | 15.25 oz| 10.00            | $0.89              | $8.90      |
| Corn, Sweet Whole Kernel Golden, Kroger   | 15.25 oz| 23.00            | $0.69              | $15.87     |
| Green Beans, Cut, Kroger                  | 14.5 oz| 10.00              | $0.69              | $6.90      |
| Hash Browns, Kroger Country Style          | 30 oz| 7.00                | $1.99              | $13.93     |
| Pasta Sauce, Rinaldi Tomato & Basil       | 24 oz| 10.00              | $2.49              | $24.90     |
| Salsa, Pace Chunky, Medium (Jar)          | 16 oz| 10.00              | $2.49              | $24.90     |
| Pasta, Thin Spaghetti, Kroger             | 16 oz| 6.00                | $1.00              | $6.00      |
| Tortilla Chips, Corn, Signature SELECT    | 10.5 oz| 13.00            | $1.50              | $19.50     |
| Cereal, Kroger Crunchy Raisin Bran        | 18.2 oz| 2.00              | $2.99              | $4.58      |
| Cereal, Post Original Grape-Nuts          | 20.5 oz| 2.00              | $4.19              | $8.38      |
| Oats, 100% Whole Grain, Kroger            | 42 oz| 1.00                | $4.39              | $4.39      |
| Total                                     |      |                     |                    | $631.52    |
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