Optimizing Balanced Meal Plans Using Linear Programming

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Abstract

Meal planning is a fundamental step in maintaining a healthy diet. Despite widespread nutritional guidelines, people on a diet often struggle to design low-calorie and nutritionally adequate meals. This study addresses this challenge by applying linear programming (LP) to optimize meal composition. The model minimizes caloric intake while ensuring each meal meets specific nutrient and fiber targets—30g of protein, 30g of carbohydrates, 10g of fat, and 10g of fiber—using a diverse selection of whole foods.

The results show that nutritionally complete meals can be designed within a 280–330 kcal range by strategically combining proteins (e.g., tofu, shrimp), vegetables (e.g., broccoli, spinach), and smart carbohydrate sources (e.g., lentils, quinoa). Notably, the model's sensitivity to dietary restrictions like vegetarian or dairy-free diets was evaluated, revealing minimal caloric trade-offs. This suggests that LP can flexibly accommodate real-world dietary needs while maintaining nutritional balance.

Beyond theoretical optimization, this approach offers practical value. It provides a science-backed method to design balanced meals for health-conscious people with dietary restrictions. For nutrition professionals, it serves as a tool to create personalized meal plans that adhere to specific health goals. The study bridges the gap between computational optimization and everyday eating, demonstrating how math can make creating healthy diets easier.

Keywords: meal planning, nutrition optimization, linear programming, dietary analysis

1. Introduction

Designing nutritionally adequate meals is not easy. While dietary guidelines provide recommendations, such as consuming adequate protein or limiting added sugars, they rarely address how to translate these guidelines into practical meal compositions. This gap between theory and practice often results in people not getting enough essential nutrients or eating too many calories while trying to meet their dietary goals.

Traditional approaches to meal planning rely on simple rules of thumb, like the 'plate model' that divides a plate into sections for protein, carbs, and vegetables, or using pre-set meal templates. While helpful, these methods don't account for the specific nutritional makeup of individual foods. For example, 100 grams of chicken breast provides 31 grams of protein and no carbs, while the same amount of lentils has 9 grams of protein plus 20 grams of carbs. These differences are important when trying to build meals that meet precise nutrition goals without extra calories.

Linear programming provides a systematic way to combine different foods to meet nutritional goals. Instead of relying on trial-and-error methods, LP finds the best combinations by minimizing calories while ensuring sufficient nutrients and fiber. While dietitians similarly plan meals, the added computational power of linear programming allows for faster and more tailored meal recommendations.

Research questions:

- How can LP be used to design minimal-calorie meals that meet nutritional targets?
- How does adjusting nutrient requirements influence meal composition and caloric intake?
- Can this method accommodate common dietary restrictions, such as vegetarianism or lactose intolerance, without compromising nutritional adequacy?

2. Literature Review

The application of mathematical optimization to nutrition is not new but has gained renewed interest with advances in computational power and dietary science. Early work by Stigler (1945) and later by Dantzig (1990) set the stage for using linear programming to minimize costs while meeting nutritional needs. Although these studies were groundbreaking, they relied on overly simplistic food databases and focused mainly on cost, rather than overall diet quality.

Contemporary research has expanded on this foundation. For instance, Maillot et al. (2007) demonstrated how LP could design nutrient-dense diets that align with dietary guidelines, highlighting the importance of food diversity in meeting nutrient needs that is often overlooked in earlier models. Similarly, Perignon et al. (2016) applied optimization to create environmentally sustainable meal plans, illustrating how LP can balance multiple objectives beyond nutrition.

Gaps remain in the literature, as many models rely on abstract or outdated food lists that don't align with modern eating patterns. Some focus narrowly on single nutrients instead of comprehensive meal composition, while others fail to consider practical constraints like dietary restrictions or food preferences. This project addresses these limitations by incorporating a diverse, whole-foods-based database and testing the model's flexibility under different nutritional targets and dietary restrictions, aiming to create a tool that works well in the real world and is backed by solid science.

3. Methodology

Database Development

For this project, 38 commonly consumed foods (Table 1) were selected across major dietary categories: proteins, vegetables, healthy fats, and grains. Each food was labeled by its serving size in grams and nutritional content per serving, including calories, protein, carbohydrates, fats, and fiber. This database was designed to reflect realistic foods rather than idealized ingredients. For example, whey protein powder is a concentrated source of protein, but it was excluded in favor of whole-food options like Greek yogurt and cottage cheese. This ensures the model's outputs are practical for everyday cooking.

Model Formulation

Objective Function:

Minimize the sum of calories from selected foods

Constraints:

- Protein ≥ 30g
- Carbohydrates ≥ 30g
- Fats ≥ 10g
- Fiber ≥ 10g
- Total meal weight ≤ 600g
- Include at least 3 different food items
- Include foods from at least 4 different food groups

The model was done in Python using the PuLP library, which provides an environment for defining and solving linear programs.

Sensitivity Analysis

Sensitivity analysis is conducted to explore how adjusting nutritional targets and applying dietary restrictions would affect meal composition.

First test: Baseline scenarios used standard targets of 30g of protein and 30g of carbohydrates. Variations tested protein levels of 25g, 30g, and 35g, alongside carbohydrate levels of 20g, 30g, and 40g.

Second test: Dietary restrictions, such as vegetarian, legume-free, and dairy-free options, were included. Each scenario demonstrated how shifting nutrient targets or excluding specific food groups can reshape meal composition, highlighting the trade-offs and flexibility in achieving balanced diets.

4. Results and Discussion

Optimal Meal Compositions

The model generated the top 5 nutritionally balanced meals within the 280–330 kcal range.

- Meal 1:

Tempeh (74g), broccoli (72g), spinach (200g), Brussels sprouts (54g), and mushrooms (200g). This meal provides 280.5 kcal, 29.9g of protein, 30g of carbs, 10g of fat, and 10.3g of fiber. Including mushrooms and spinach adds micronutrients without significantly increasing calories, illustrating how vegetables can boost meal volume and nutrition while maintaining low energy density.

- Meal 2:

Tofu (13g), shrimp (99g), lentils (3g), zucchini (200g), avocado (51g), and strawberries (234g). This meal provides 305 kcal, 30.1g of protein, 30g of carbs, 10g of fat, and 10g of fiber. Avocado contributes healthy fats, while strawberries add extra fiber, which shows how fruits can be seamlessly included in savory meals.

These examples output (Figure 1) highlight a key insight that meals do not need to be restrictive or bland to meet nutritional targets. By leveraging food pairings, the model achieved balance without relying on processed or artificial ingredients.

Sensitivity to Macronutrient Targets

- Adjusting protein and carbohydrate requirements (Table 3, Figure 2)

The sensitivity analysis revealed that adjusting protein and carbohydrate targets had a surprisingly subtle impact on the core ingredients chosen. When protein was increased from 30g to 35g, the model primarily adjusted portion sizes of high-protein ingredients like tofu or shrimp, while still maintaining the same basic set of vegetables and supporting foods. Similarly, reducing carbohydrates to 20g led to modest decreases in carbohydrate-dense vegetables like broccoli and Brussels sprouts, while slightly increasing leafy greens like spinach and adding more of low-carb options like mushrooms, without introducing completely new ingredients. This suggests that the model's core food database was robust and balanced enough to absorb these nutrient shifts simply by tweaking the quantities of existing ingredients, rather than needing to find entirely new food sources.

Dietary Restrictions

- Vegetarian, Legume-Free, and Dairy-Free (Table 4)

The sensitivity analysis for dietary restrictions revealed minimal changes in meal composition and nutrient profiles. Despite excluding legumes or dairy, the model consistently relied on a core set of plant-based ingredients: tempeh, broccoli, spinach, Brussels sprouts, and mushrooms. Only the vegetarian scenario included tofu, which was used as a convenient plant-based protein source to meet the 30g protein target without relying on animal-based proteins. In contrast, the no-dairy scenario excludes tofu is not due to dietary restrictions, since tofu is dairy-free, but because the optimizer found that the other ingredients already met the nutritional targets. This stability in ingredient choice underscores the flexibility of the selected food database, which can accommodate various dietary constraints by adjusting the relative quantities of existing ingredients rather than requiring major substitutions. It demonstrates how well-designed dietary optimization can adapt to different restrictions while preserving nutritional balance and meal integrity.

These adaptations demonstrate the model's flexibility and its potential to support diverse dietary preferences without sacrificing nutritional quality.

5. Practical Applications and Limitations

The project demonstrates practical insights for individuals and nutrition professionals. For everyday eating, it provides a blueprint for building balanced meals without guesswork, showing how plant-based proteins like tempeh and lentils can offer comparable protein to animal sources with fewer calories, ideal for weight management. Non-starchy vegetables such as spinach and mushrooms add volume and essential nutrients without significantly boosting calories, while whole grains and legumes provide fiber and sustained energy without the blood sugar spikes of refined carbs. For nutrition professionals, the model demonstrates how adjusting constraints can help make meal plans to individual goals, whether for weight loss, athletic performance, or managing conditions like diabetes.

However, there are some limitations to the model. For example, it doesn't yet include detailed nutrients like vitamins and minerals. Future improvements include integrating individual calorie needs and allergy profiles, linking optimized ingredients to real-world recipes for practical use, and incorporating sustainability metrics like carbon footprint to create more personalized dietary solutions.

6. Conclusion

The model demonstrates that linear programming is more than an academic exercise; it’s a practical tool for solving everyday dietary challenges. By systematically evaluating how foods combine to meet nutritional needs, the model removes much of the uncertainty from meal planning.

The most compelling finding is that balanced and satisfying meals can be created even within modest caloric limits. Whether the goal is weight management, athletic performance, or overall health, strategic food choices matter more than extreme dietary restrictions. Even when accounting for dietary preferences or limitations, small adjustments ensure nutritional adequacy, offering a sustainable path to healthier eating.

For people who feel overwhelmed by conflicting nutrition advice, this meal optimization approach offers clear solutions. In a world where diet-related diseases are widespread, these tools empower individuals to take charge of their health, one thoughtfully balanced meal at a time.

References

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Appendices

	Food	Food_Group	Serving_Description	Calories	Protein_g	Carbs_g	Fats_g	Fiber_g
0	Chicken Breast	Protein	100g (standard portion)	165	31.0	0.0	3.6	0.0
1	Salmon	Protein	100g (standard portion)	208	20.0	0.0	13.0	0.0
2	Egg Whites	Protein	100g (standard portion)	52	11.0	0.7	0.2	0.0
3	Whole Eggs	Protein	50g (typical serving)	72	6.3	0.4	5.0	0.0
4	Lean Ground Turkey	Protein	100g (standard portion)	135	22.0	0.0	5.0	0.0
5	Lean Beef	Protein	100g (standard portion)	158	26.0	0.0	6.0	0.0
6	Tofu	Protein	100g (standard portion)	76	8.1	1.9	4.8	0.3
7	Tempeh	Protein	100g (standard portion)	193	19.0	9.0	11.0	0.0
8	Shrimp	Protein	100g (standard portion)	99	24.0	0.2	0.3	0.0
9	Greek Yogurt	Dairy	150g (typical serving)	100	17.0	6.0	0.0	0.0
10	Cottage Cheese	Dairy	100g (standard portion)	98	11.0	3.4	4.3	0.0
11	Milk	Dairy	240g (typical serving)	103	8.0	12.0	2.4	0.0
12	Brown Rice	Grain	100g (standard portion)	111	2.6	23.0	0.9	1.8
13	Quinoa	Grain	100g (standard portion)	120	4.4	21.3	1.9	2.8
14	Sweet Potato	Vegetable	100g (standard portion)	86	1.6	20.1	0.1	3.0
15	Whole Wheat Pasta	Grain	100g (standard portion)	131	5.0	25.0	1.0	3.0
16	Oats	Grain	40g (typical serving)	150	5.0	27.0	2.5	4.0
17	Black Beans	Legume	100g (standard portion)	132	8.9	23.7	0.5	8.7
18	Lentils	Legume	100g (standard portion)	116	9.0	20.0	0.4	7.9
19	Chickpeas	Legume	100g (standard portion)	164	8.9	27.0	2.6	7.6
20	Broccoli	Vegetable	100g (standard portion)	34	2.8	6.6	0.4	2.6
21	Spinach	Vegetable	100g (standard portion)	23	2.9	3.6	0.4	2.2
22	Kale	Vegetable	100g (standard portion)	35	2.9	4.4	0.5	2.0
23	Brussels Sprouts	Vegetable	100g (standard portion)	43	3.4	8.9	0.3	3.8
24	Carrots	Vegetable	100g (standard portion)	41	0.9	9.6	0.2	2.8
25	Bell Peppers	Vegetable	100g (standard portion)	31	1.0	6.0	0.3	2.1
26	Zucchini	Vegetable	100g (standard portion)	17	1.2	3.1	0.3	1.0
27	Mushrooms	Vegetable	100g (standard portion)	22	3.1	3.3	0.3	1.0
28	Avocado	Healthy Fat	50g (typical serving)	80	1.0	4.0	7.5	3.0
29	Almonds	Healthy Fat	30g (typical serving)	170	6.0	6.0	15.0	3.5
30	Walnuts	Healthy Fat	30g (typical serving)	185	4.3	3.9	18.5	2.0
31	Peanuts	Healthy Fat	30g (typical serving)	166	7.0	6.0	14.0	2.4
32	Olive Oil	Healthy Fat	15g (typical serving)	120	0.0	0.0	14.0	0.0
33	Flaxseeds	Healthy Fat	10g (typical serving)	55	1.9	3.0	4.0	2.8
34	Chia Seeds	Healthy Fat	10g (typical serving)	50	1.7	4.0	3.0	3.4
35	Pumpkin Seeds	Healthy Fat	10g (typical serving)	56	5.0	1.0	4.0	0.5
36	Blueberries	Fruit	150g (typical serving)	85	1.1	21.0	0.5	3.6
37	Strawberries	Fruit	150g (typical serving)	50	1.0	12.0	0.5	3.0

- Table 1

	Calories			Protein_g	Serving_Size_g
	mean	min	max	mean	mean
Food_Group					
Dairy	100.3	98	103	12.0	163.3
Fruit	67.5	50	85	1.0	150.0
Grain	128.0	111	150	4.2	85.0
Healthy Fat	110.2	50	185	3.4	23.1
Legume	137.3	116	164	8.9	100.0
Protein	128.7	52	208	18.6	94.4
Vegetable	36.9	17	86	2.2	100.0

- Table 2

	Protein (g)	Carbs (g)	Calories	Foods
0	25	20	232.9	Tofu, Shrimp, Spinach, Brussels Sprouts, Mushrooms, Avocado
1	25	30	260.4	Tofu, Broccoli, Spinach, Brussels Sprouts, Mushrooms, Walnuts
2	25	40	292.1	Tofu, Broccoli, Spinach, Brussels Sprouts, Mushrooms, Walnuts
3	30	20	252.9	Tofu, Shrimp, Spinach, Brussels Sprouts, Mushrooms, Avocado
4	30	30	278.5	Tofu, Broccoli, Spinach, Mushrooms, Walnuts
5	30	40	310.1	Tofu, Broccoli, Spinach, Brussels Sprouts, Mushrooms, Walnuts
6	35	20	273.0	Tofu, Shrimp, Spinach, Brussels Sprouts, Mushrooms, Avocado
7	35	30	298.2	Tofu, Shrimp, Broccoli, Spinach, Mushrooms
8	35	40	328.6	Tofu, Shrimp, Broccoli, Spinach, Brussels Sprouts, Mushrooms

- Table 3

	Diet	Calories	Protein (g)	Foods
0	Vegetarian	281.4	30.1	Tofu, Tempeh, Broccoli, Spinach, Brussels Sprouts, Mushrooms
1	No_Legumes	280.5	29.9	Tempeh, Broccoli, Spinach, Brussels Sprouts, Mushrooms
2	No_Dairy	280.5	29.9	Tempeh, Broccoli, Spinach, Brussels Sprouts, Mushrooms

- Table 4

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=== OPTIMAL MEAL PLAN #1 ===

Ingredients:
Tempeh                0.74 servings (74.0g)
Broccoli              0.72 servings (72.0g)
Spinach               2.00 servings (200.0g)
Brussels Sprouts      0.54 servings (54.0g)
Mushrooms             2.00 servings (200.0g)

Nutritional Summary:
Calories: 280.5 kcal
Protein: 29.9g
Carbs: 30.0g
Fats: 10.0g
Fiber: 10.3g

Total Weight: 600.0g
Food Groups: Protein, Vegetable
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=== OPTIMAL MEAL PLAN #2 ===

Ingredients:
Tofu                  0.13 servings (13.0g)
Shrimp                0.99 servings (99.0g)
Lentils               0.03 servings (3.0g)
Zucchini              2.00 servings (200.0g)
Avocado               1.02 servings (51.0g)
Strawberries          1.56 servings (234.0g)

Nutritional Summary:
Calories: 305.0 kcal
Protein: 30.1g
Carbs: 30.0g
Fats: 10.0g
Fiber: 10.0g

Total Weight: 600.0g
Food Groups: Healthy Fat, Fruit, Vegetable, Protein, Legume
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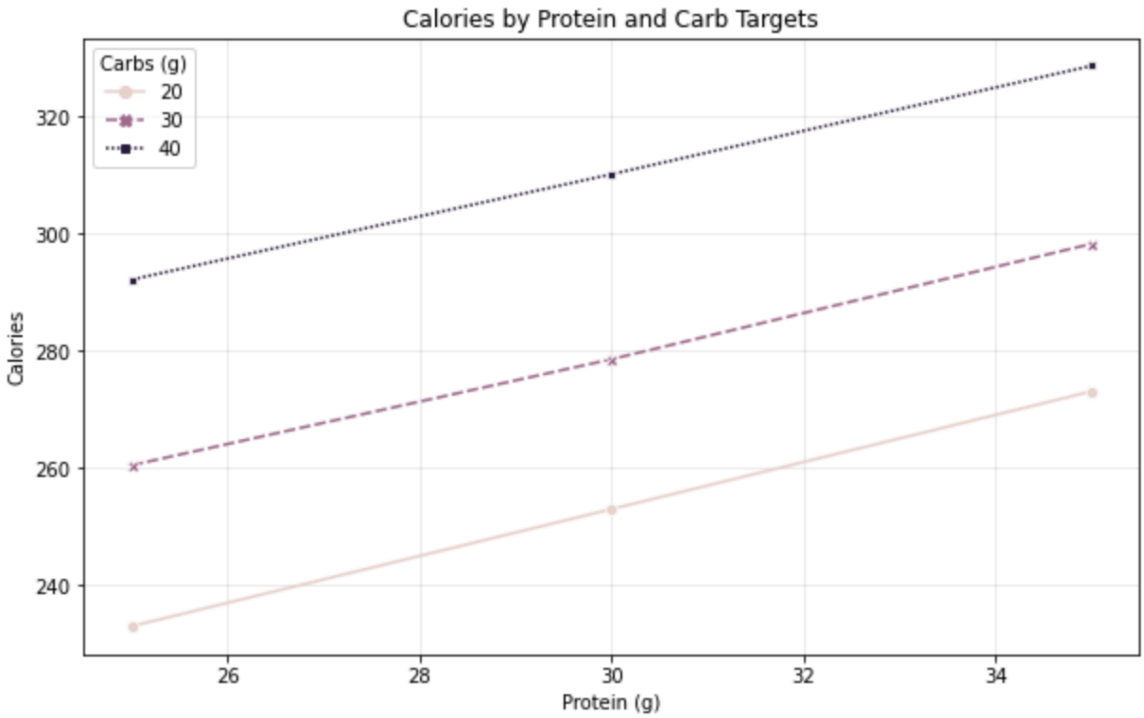
- Figure 1



Calories by Protein and Carb Targets
Carbs (g)
20
30
40
320
300
280
260
240
Calories
26
28
30
32
34
Protein (g)

- Figure 2