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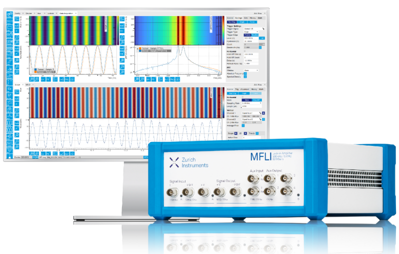

Vertex Coloring in Graphs: A Novel Approach to Nutritional Menu Planning

Siti Amiroch,[1, a)] Huilan Chang,[2] Mohammad Jamhuri,[3] and Toni Yulianto[4]

[1]*Department of Mathematics, Universitas Islam Darul Ulum Lamongan, Lamongan, Indonesia*
[2]*Department of Mathematics, National University of Kaohsiung, Kaohsiung, Taiwan*
[3]*Department of Mathematics, UIN Maulana Malik Ibrahim Malang, Malang, Indonesia*
[4]*Department of Mathematics, Universitas Islam Madura, Madura, Indonesia*

[a)]Corresponding author: siti.amiroch@unisda.ac.id

Abstract. In this study, we propose a novel method for creating nutritious menus using vertex coloring, a fundamental concept in graph theory. Our team has combined the Welch-Powell algorithm with a mathematical combination technique to generate a range of menus that adhere to low-calorie nutritional guidelines while offering diversity. To showcase the practicality and efficacy of our approach, we have utilized dynamic simulation in Matlab, which generates three distinct diet combinations customized to meet specific nutritional needs. Our methodology can serve as a blueprint for developing balanced meal plans and underscores the flexibility of graph theory in real-world applications. Additionally, we have explored an alternative approach to arranging menus that employ vertex-disjoint paths in a graph, resulting in a streamlined process for creating diverse and nutritionally balanced menus. This study highlights the significance of innovative solutions for addressing the complexities of diet planning and provides valuable insights for future research.

INTRODUCTION

Graph theory and dietary planning can be combined to address the complexities of nutritional balance. In this work, we explore the application of vertex coloring in graph theory to enhance menu planning strategies. The focus is on achieving optimal nutrient intake and absorption. Traditional dietary planning often overlooks the critical aspect of calorie content, leading to nutritional imbalances [1]. This study aims to bridge this gap by incorporating graph-theoretical concepts and offering a systematic approach to meal composition.

Graph theory, renowned for solving intricate combinatorial problems, offers a robust framework for this endeavor [2]. We introduce a graph G, denoted as $G = (V, E)$, wherein each vertex V symbolizes a distinct food item, and the edges E represent the nutritional compatibility between these items. The process of vertex coloring, based on Gross (2018), assigns unique colors to each vertex such that no two adjacent vertices share the same color, ensuring a diverse and nutritionally balanced meal composition [3], [4].

The application of vertex coloring extends beyond its traditional realms in computer science, encompassing a wide range of problems from scheduling to network optimization [5]. Recognized as a challenging combinatorial optimization problem [6] and closely associated with minimal coloring concepts [7], vertex coloring in this context serves as a tool for methodically arranging balanced food menus.

This study contrasts traditional menu planning approaches, often sidelining calorie considerations, as highlighted by Joanne and Rebecca [8], and adopts a different perspective. By integrating the principles of vertex coloring, as explored in the works of Amiroch and Andini [9], with a focus on calorie content, this approach links to broader graph theory concepts like matching in bipartite graphs [10] and Hall's Theorem [11], providing a framework for caloric adequacy in menu planning.

This research thus extends the utility of vertex coloring, a tool predominantly utilized in computer science and scheduling, to the practical and critical field of diet planning [12]. We propose a unique methodology for constructing varied and nutritionally complete menus, employing the Welch-Powell algorithm and other mathematical strategies in menu arrangement [13], [14].

Integrating vertex coloring and graph theory with dietetics showcases the versatility of mathematical approaches and opens new avenues for practical applications in everyday nutrition planning [15].

METHODS

This research employs graph theory to innovate nutritional menu planning, utilizing two methodologies: vertex coloring on a graph and vertex-disjoint paths in a graph. Both methods are detailed below.

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Vertex Coloring on a Graph

The data for this study were sourced from the dietary habits of the population in Lamongan, East Java, Indonesia [9], with calorie content information obtained from the official health website www.kemkes.go.id. The methodology involved several key steps:

1. **Listing of Menu Items:** Menu items were classified into carbohydrates, dishes, vegetables, fruits, and drinks, each including calorie information. The menus consisted of different combinations for breakfast, lunch, and dinner, with total combinations calculated using the multiplication rule [16].
2. **Combining Menus with Calorie Consideration:** Menus were strategically combined to meet specific calorie targets for each meal: 500-600 calories for breakfast, 400-550 calories for lunch, and 300-450 calories for dinner [17].
3. **Menu Selection Process:** Menus were selected and prepared to meet balanced calorie needs. In this process, a complete daily menu was represented by V (vertex), and individual meal menus by E (edge) [18].
4. **Application of Vertex Coloring:** The Welch Powell Algorithm was used for menu diversification. This involved ordering the vertices of graph G by decreasing degree, coloring them systematically, and ensuring no adjacent vertices shared the same color.

Vertex-Disjoint Paths in a Graph

Sets B, L, and D were defined to represent breakfast, lunch, and dinner menus, each adhering to specific calorie constraints. These sets were transformed into vertices of a multipartite graph, $G[B,L,D]$. The construction of this graph and the identification of vertex-disjoint paths for balanced diet planning involved:

1. **Finding Maximum Matching:** A maximum matching, M, was identified in the subgraph of $G[B,L,D]$ induced by $B \cup L$.
2. **Identifying Saturated Set and Second Matching:** The set L' included vertices in L saturated by M. A second maximum matching, M', was then found in the subgraph induced by $L' \cup D$.
3. **Combining Matchings for Vertex-Disjoint Paths:** The combination of M and M' represented diverse menu combinations as vertex-disjoint paths.

Hardware and Software Utilized

To implement our methodologies, we employed specific hardware and software to ensure accurate data processing and analysis.

- **Hardware:** The experiment used a Dell computer with an Intel Core i5 8th Generation processor and 8GB of memory. This configuration provided the necessary computational power to efficiently handle graph algorithms and data analysis tasks.
- **Software:**
  - *Graph Theory Analysis:* MATLAB 2020 was used to implement vertex coloring and vertex-disjoint path calculations. This software offers robust functionality for graph-based computations and mathematical modeling.
  - *Data Management:* MATLAB 2020 was also utilized for managing and analyzing the dietary data. Its versatile environment facilitated the organization, storage, and retrieval of complex nutritional data sets.
  - *Algorithm Implementation:* The Welch Powell Algorithm and other graph-theoretical computations were executed within the MATLAB environment, taking advantage of its efficient processing capabilities for algorithmic operations.

The combination of this specific hardware and MATLAB 2020 software played a pivotal role in successfully executing our research, ensuring accuracy and efficiency in data processing and analysis.

RESULTS

Results from Matlab Simulation

This study employed a Matlab simulation to design meals within the calorie range of a low-calorie diet, which is suggested to be between 1000 and 1700 calories daily. Adhering to the principles of a healthy and balanced meal habit, the caloric distribution was as follows [19]:

$$\sum \text{breakfast calories} > \sum \text{lunch calories} > \sum \text{dinner calories} \tag{1}$$

1. **Simulation Process and GUI Interaction:** The simulation, leveraging vertex coloring via the Welch Powell algorithm, was made dynamic and user-friendly through a Graphical User Interface (GUI). The GUI in Figure 1 allowed users to set the menu for a specified number of days and input minimum and maximum values based on established balanced menu calorie rules. For instance, entering ’8’ would set the menu for eight days. The simulation presented 50 menu options for each meal, which could be further narrowed down to the top ten preferred options.

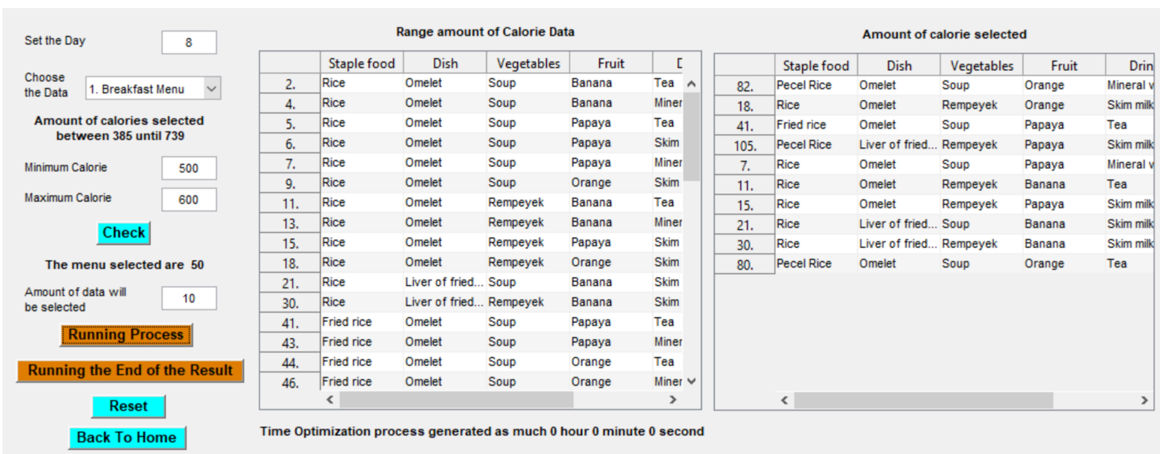

FIGURE 1. GUI of the Breakfast Menu

2. **Lunch and Dinner Menu Selection:** In the lunch menu selection phase (see Figure 2), the calorie range was observed between 351.5 and 756.5. Based on the calorie rule for lunch, the input range was adjusted from 350 minimum to 550 maximum calories, resulting in 88 selected menus. From these, ten were chosen.

   The dinner menu (see Figure 3) presented 16 options with calorie counts ranging from 324 to 457.5. After inputting a calorie range of 350 to 450, 13 menus were selected.

3. **Complete Menu Arrangement for Eight Days:** Upon selecting breakfast, lunch, and dinner menus, the ’Running process’ and ’Running the end of the result’ buttons in the GUI provided a comprehensive eight-day menu list, as depicted in Figure 4.

   This list displayed a variety of menu items for each meal across eight days, marked as $x_1 \to x_{10}$ for breakfast, $y_1 \to y_{10}$ for lunch, and $y_1 \to z_{10}$ for dinner. The adjacent vertex graph below represents the menu arrangement over these eight days.

4. **Menu Variability and Chromatic Numbers:** Each node in Figure 5 represents a different day, with various menus ensuring distinct meals each day, although some repeats occurred. The Table 1 below summarizes the eight-day menu arrangement:

   The variety of the menu combinations increases with the number of days, leading to repetitions if the number of selected daily menus is exceeded. The simulation effectively arranges the menus and calorie content per serving, as demonstrated in the 30-day menu arrangement graph (see Figure 6).

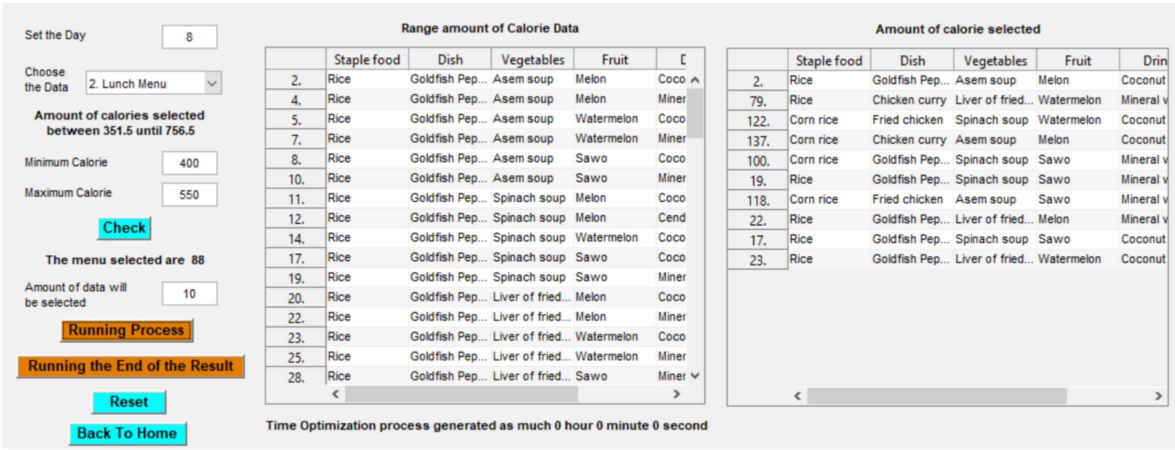

FIGURE 2. GUI of the Lunch Menu

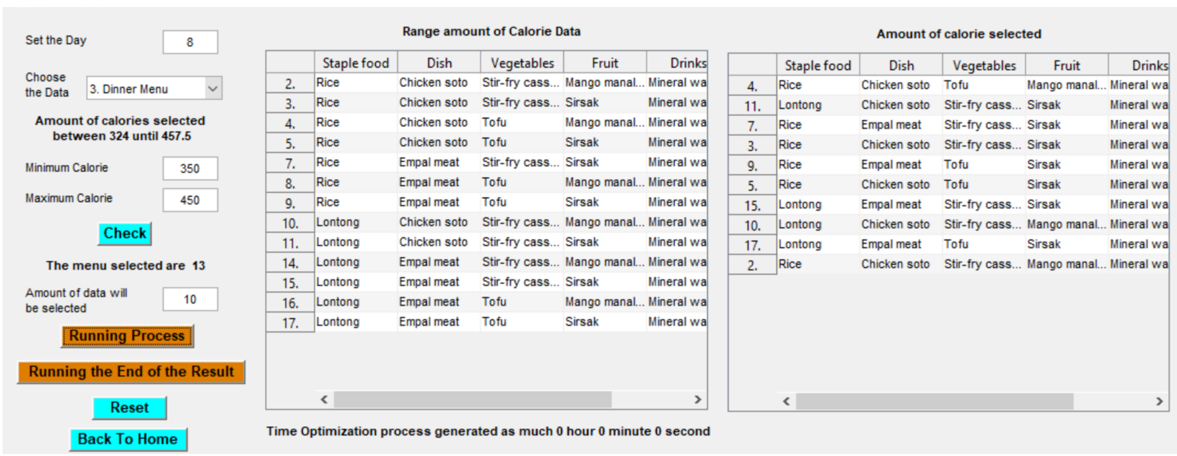

FIGURE 3. GUI of the Dinner Menu

In Figure 6, seven colors indicate the menu arrangement based on dates or days. For 30 days, menus are set based on the date, as shown in the Table 2.

5. **Calorie Counts and Menu Data:** The number of menus and calorie requirements per serving are detailed in Table 3.

   *The menu list is adjusted according to the calorie needs. **The minimum calorie requirement for dinner is 300, but the data shows a minimum of 324 calories; hence, 350 calories were taken as the minimum.

6. **Chromatic Numbers:** The chromatic number, indicative of the diet menu's calorie arrangement, is summarized in the Table 4 below:

The simulation results underscore the method's effectiveness in curating diverse menus, focusing on calorie considerations and meal variety.

Result from Vertex-Disjoint Paths of a Graph

This section elucidates the process of selecting menu combinations based on the body's caloric needs at each meal, utilizing graph theory concepts. Specifically, 'Matching' in the graph is employed to ensure diverse menu selections

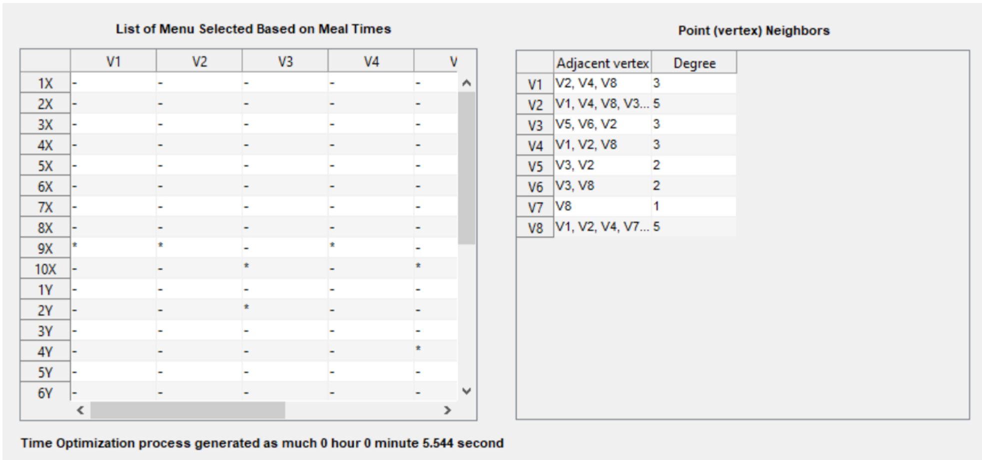

FIGURE 4. GUI with a List of Selected Menus Based on Meal Times

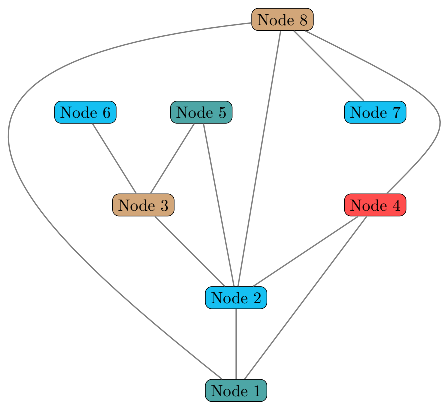

FIGURE 5. Graph of the Menu Arrangement for Eight Days

across different days, while the Depth First Search (DFS) algorithm is used to generate paths representing menu dish combinations for three daily servings.

1. **Menu Determination in Matlab Simulation:** In our Matlab-simulated application, menu choices are made randomly due to the extensive range of possible combinations. The underlying matching analysis explains this random selection process. The relationship between the number of menus and the required calories per serving, as presented in Table 3, is formulated as follows:

$$\begin{array}{ccccccc|ccc|cc} 385 & \leq & x_1 & x_2 & x_3 & x_4 & x_5 & \dots & x_{108} & \leq & 739 \\ 351.5 & \leq & y_1 & y_2 & y_3 & y_4 & y_5 & \dots & y_{162} & \leq & 756.5 \\ 324 & \leq & z_1 & z_2 & z_3 & z_4 & z_5 & \dots & z_{16} & \leq & 457.5 \end{array} \tag{2}$$

   Where:

   - $x_1, x_2, \dots, x_{108}$ is represented 1st until 108th breakfast menu.
   - $y_1, y_2, \dots, y_{162}$ is represented 1st until 162th breakfast menu.
   - $z_1, z_2, \dots, z_{16}$ is represented 1st until 16th breakfast menu.

2. **Caloric Range and Probability of Menu Selection:** Equation (2) is adjustable based on the available menu options within a specified caloric range. The lines in Equation (2) indicate an attempt to minimize the caloric

TABLE 1. The result of the arrangement menu as long as eight days

The color	Node/vertex	Consumed
Tosca green	V1, V5	Monday1, Tuesday2
Light blue	V6, V2, V7	Wednesday1, Thursday1, Friday1
Red	V4	Saturday1
Brown	V3, V8	Sunday1, Monday2

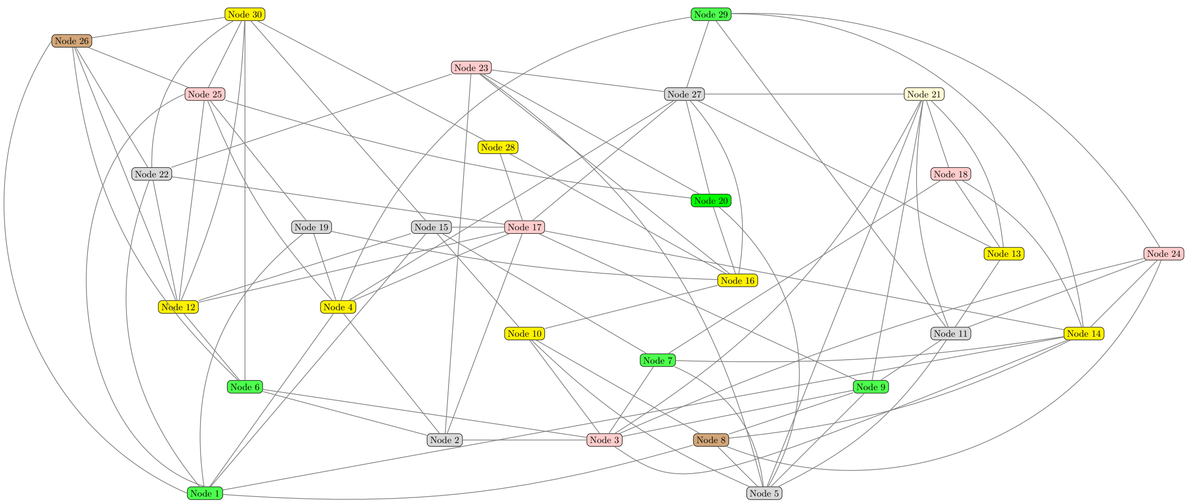

FIGURE 6. Result of the Menu Arrangement for 30 Days

scope. Further details are provided in Figure 7, where the left-hand value represents the minimum calorie value from each food serving as per a balanced diet, and the right-hand value denotes the maximum set value. The probability of selecting a particular menu is depicted in the subsequent equation:

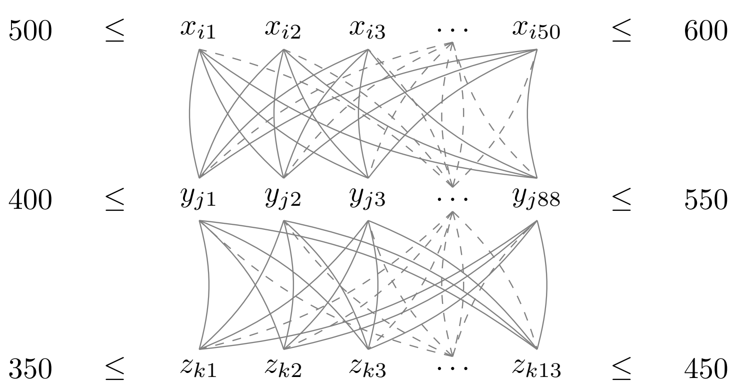

FIGURE 7. Caloric Range and Probability of Menu Selection

3. **Illustration of Bipartite Graphs and Menu Combinations:** The graph illustrates the probability of menu selection for each meal. Each vertex in set X is freely paired with vertices in sets Y and Z, without limitations imposed by the total daily calorie count, as the caloric intake is restricted per serving. This pairing forms two bipartite graphs, with each combination also representable as a path, exemplified in the following formulas (3):

TABLE 2. The result of the arrangement menu as long as 30 days

The color	Node/vertex	Consumed
Light yellow	V4, V10, V13, V14, V16, V30	The 1st until the 6th day
Red	V3, V18, V23, V24, V25, V17	The 7th until the 12th day
Light green	V1, V7, V9, V20, V29, V6	The 13th until the 18th day
Dark blue	V11, V15, V22, V27	The 19th until the 22nd day
Yellowish green	V28, V21, V12	The 23rd until the 25th day
Purple	V2, V5, V19	The 26th until the 28th day
Brown	V26, V8	The 29th until the 30th day

TABLE 3. The number of menus and calories needed per serving

Menu	Amount of data	Variety Menu	Calories	Min_Cal Needed	Max_Cal Needed	List of Menu*
Breakfast	3,3,3,2,2; (13)	108	385 - 739	500	600	50
Lunch	3,3,3,3,2; (14)	162	351.5 – 756.5	400	550	88
Dinner	2,2,2,2,1; (9)	16	324 – 457.5	350**	450	13

$$\begin{array}{r|l} \text{Day } 1 & x_{i1}y_{j1}z_{k1} \\ \text{Day } 2 & x_{i2}y_{j2}z_{k2} \\ \text{Day } 3 & x_{i3}y_{j3}z_{k3} \\ \vdots & \quad\vdots \\ \text{Day } n & x_{in}y_{jn}z_{kn} \end{array} \left.\vphantom{\begin{array}{l} 1\\2\\3\\ \vdots \\ n \end{array}}\right\} \qquad \boxed{\text{Paths}} \tag{3}$$

4. **Application of Depth First Search and Matching:** The DFS algorithm facilitates the generation of a path that represents a sequence of menu combinations for three servings per day. Concurrently, 'Matching' ensures that the chosen menu combinations vary daily, whether for breakfast, lunch, or dinner. Through 'Matching,' intersections between elements are avoided, promoting variety in the diet plan.

DISCUSSION

The results from the Matlab simulation, particularly the use of vertex coloring with the Welch-Powell algorithm, demonstrate a promising approach to personalized and dynamic menu planning. The ability of the simulation to adapt to user inputs, as indicated by the varied menu options and the flexibility in setting meal plans for different days, underscores its potential utility in dietary planning. The graphical user interface (GUI) enhances user interaction, making the process of meal planning more accessible and tailored to individual dietary needs.

The simulation's capacity to offer a wide range of menu combinations, as evidenced by the GUI outputs for breakfast, lunch, and dinner, aligns with the principle of a balanced and varied diet. This aligns with nutritional guidelines advocating diversity in food choices to ensure a comprehensive nutrient intake. The ability to filter and refine menu options based on calorie content further ensures adherence to dietary recommendations for low-calorie diets, which is important for weight management and chronic disease prevention.

Applying vertex-disjoint paths in graphs for menu selection reveals an innovative method of ensuring diversity in meal combinations. The use of 'Matching' to vary menus daily addresses the common challenge in meal planning of repetitive and monotonous diets, which can be a barrier to dietary adherence. The Depth First Search (DFS) algorithm's role in generating these paths indicates a robust approach to exploring all possible menu combinations, enhancing the novelty of each day's meal plan.

The ability to adjust menu selections based on caloric range and to visualize these choices through bipartite graphs not only simplifies the complex process of dietary planning but also provides a clear understanding of how different meals contribute to overall daily caloric intake. This approach is particularly beneficial in managing diets where caloric control is crucial, such as diabetes or obesity.

The combination of Matlab simulation and graph-theoretical approaches in dietary planning opens new avenues in nutrition and dietetics. It showcases the potential of integrating technology and advanced mathematical algorithms

TABLE 4. Chromatic number according to menus selected

Set the day	Breakfast menu selected	Lunch menu selected	Dinner menu selected	Chromatic number	Time of process
10	10	10	10	4	5,544
15	8	10	5	5	1,035
20	15	10	8	5	0,735
25	10	12	5	8	1,298
30	10	10	8	7	1,593

in creating practical, personalized, and varied diet plans. This method also offers a novel tool for dietitians and nutritionists, potentially enhancing the effectiveness and appeal of dietary interventions.

Future research could explore the integration of more complex nutritional parameters, such as macronutrient ratios or specific dietary requirements for various health conditions. Expanding the user interface to include more interactive features and integrating feedback mechanisms could enhance the tool's utility and user experience. The adaptability of this approach to different cultural and regional dietary preferences also warrants exploration.

In conclusion, this study demonstrates the efficacy of a graph-theoretical approach in nutritional menu planning, offering a novel perspective on the intersection of technology, mathematics, and dietetics.

CONCLUSION

This research has successfully demonstrated the integration of graph theory, specifically vertex coloring and vertex-disjoint paths, with nutritional menu planning using Matlab simulation. The study's outcomes highlight the potential of mathematical and computational approaches in revolutionizing dietary planning.

The Matlab simulation, augmented with the Welch Powell algorithm, effectively provided diverse and balanced meal options, catering to specific caloric requirements. This user-friendly approach, facilitated through a graphical user interface, allows for personalized and flexible diet planning. The ability to generate varied menus for different days adheres to nutritional guidelines for a balanced diet and addresses common challenges in meal planning, such as monotony and rigidity.

Furthermore, applying vertex-disjoint paths in graphs for menu selection has proven to be a novel method for ensuring diversity and avoiding repetition in meal combinations. This approach is particularly useful for maintaining long-term dietary adherence, which is crucial in managing health and nutrition-related issues.

The implications of this research are significant for dietetics and nutrition, offering a new tool for dietitians and nutritionists to create effective, personalized, and varied diet plans. Integrating advanced algorithms and user-friendly technology in dietary planning opens up new possibilities for personalized nutrition and health management.

In conclusion, this study not only provides a novel approach to dietary planning through the application of graph theory but also sets a foundation for future research. Further exploration into incorporating more complex nutritional data and adapting to varying dietary needs and preferences could enhance the utility and reach of this approach. This study is a testament to the potential synergy between mathematics, technology, and nutrition in advancing health and well-being.

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