A recipe-based, diet-planning modelling system

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In a recent article in the *British Journal of Nutrition*, Sklan & Dariel (1993) presented a method for diet planning employing a mixed-integer programming algorithm for meeting nutritional requirements at minimum costs for institutions or individuals. They recognized that most food items are generally consumed in whole units and as such they are represented as integer variables. However, as in most previous studies, they derived the minimum cost diets by optimizing over purchased food items. The present paper presents a computer-assisted, diet-planning modelling system for individuals by optimizing over recipes instead of food items. This is accomplished by restricting the integer programming solutions to those bundles of food that represent reasonably popular meal recipes. The modelling system is composed of three main components: recipe data entry, database management, and the model. The recipe data entry component creates and stores recipes. It also provides nutritional analysis of the recipes. The database management component creates and maintains several databases necessary to build the modelling data file. The modelling component solves the user-specified model. Currently, the model component can solve for the optimal diet by minimizing cost or minimizing cooking and preparation time. The optimal diet is prepared to satisfy the recommended nutritional guidelines for a predefined group of individuals for 1 week. The system currently has 895 popular recipes found in Hawaii. Diet plans generated using this modelling system with differing objectives are discussed and compared.

Diet-planning model: Recipes: Minimum cost: Minimum time

Minimum-cost diets have their origin in the seminal work of Nobel Laureate George Stigler (1945). Stigler (1945) formulated and provided an approximate solution to the now famous 'diet problem', which seeks the minimum cost of achieving the recommended daily allowances of nutrients known to be beneficial to humans. Since then the linear programming formulation of the classic diet problem has continued to evolve. Smith (1959), Prato (1973), Bassi (1976), Foytik (1981*a*, *b*) and Silberberg (1985) have re-estimated Stigler's (1945) original problem 'as is' or with minor changes. The common characteristic of all these studies is that they optimize over raw food materials subject to two sets of constraints. One set of constraints is used to specify the minimum nutritional requirements, and the other set is designed to raise the degree of palatability. Diets generated by these models are given in terms of raw food materials and ingredients rather than menus or recipes. Menu items are defined as mixtures of foods and ingredients, defined by recipes. While all these studies have demonstrated the surprisingly low cost of satisfying the purely nutritional needs, it remains up to the individual meal planner to construct meaningful meals from the selected raw food materials and ingredients. But in many cases there is no available technology (as represented by recipes) to convert the food materials and ingredients in a typical minimum-cost diet into palatable meals. In a recent article in the *British Journal of Nutrition*, Sklan & Dariel (1993) presented a method of diet planning employing a mixed-integer programming algorithm for meeting nutritional requirements at minimum costs for institutions or individuals. They recognized that most food items are generally consumed in whole units and as such they are represented as integer variables. Again, as in most previous studies, they derived the minimum cost diets by optimizing over purchased food items rather than menus or recipes.

Balintfy (1964) pioneered the first menu-planning model formulated as a sequential, multi-stage optimization problem to circumvent the difficulty of solving large-scale integer programs. The solution to his model minimizes cost subject to nutrition, course structure and policy constraints. Variants of his model have been primarily applied to large-scale institutional settings such as hospitals and school food services. During the 1970s, Balintfy *et al.* (1974) extended the menu-planning model to include consumer food preference maximization. The latest generation of menu-planning models, led by Lancaster (1992*b*), addressed the issues of intra-meal compatibility. Lancaster (1992*a*, *b*) provided a detailed account of the historical evolution of menu planning and diet models. Leung *et al.* (1992), using a similar approach to that of Balintfy (Balintfy, 1964; Balintfy *et al.* 1974) developed an integer programming model that uses a pool of 217 popular recipes in Hawaii to derive the minimum-cost palatable weekly menus for a family of four. The model seeks to minimize total cost while satisfying the recommended dietary allowances (RDA) established by the (US) National Research Council, Food and Nutrition Board (1989) and a predefined daily course structure.

The present study uses the same model structure as Leung *et al.* (1992) with an expanded set of 895 recipes. Also, the model has been modified for the present study to include objectives to minimize preparation time, waiting time, attentive cooking time, and/or inattentive cooking time in addition to minimizing cost. To facilitate model execution and future model update, a computer-assisted modelling system has been developed.

METHODS

The mathematical model

The method employed is an extension of the model of Leung *et al.* (1992), including several time objectives in addition to minimizing total cost. The various time objectives include minimizing preparation time, waiting time, attentive cooking time, and/or inattentive cooking time. Preparation time is defined as time necessary to gather, measure and combine ingredients before cooking. Waiting time is defined as unattended time necessary for ingredients before cooking or serving such as marinating meat or allowing bread to prove. Attentive cooking time is defined as time when the cook is actively involved in the cooking process. Inattentive cooking time is defined as the time when the cook could be absent or accomplishing other tasks during the cooking process. The integer linear programming model seeks to minimize the total cost of recipes or minimize the various time objectives involved in cooking and preparing the recipes chosen from a set of popular recipes which satisfies the RDA and a predefined course structure. The model can simply be expressed as follows:

$$\text{minimize total cost} = \sum_{j=1}^{r} C_j R_j, \tag{1}$$

or

$$\text{minimize total time} = \sum_{j=1}^{r} T_j R_j, \tag{2}$$

subject to

$$\sum_{j=1}^{r} A_{ij} R_j \geq N_i, \quad \text{for} \quad i = 1, 2, \ldots, n, \tag{3}$$

$$\sum_{j=1}^{r} A_{1j} R_j \leq U_1, \quad \text{for energy intake } (i = 1) \text{ upper bound}, \tag{4}$$

$$\sum_{j=1}^{r} A_{2j} R_j \leqslant 0{\cdot}30 \left[\sum_{j=1}^{r} A_{1j} R_j \right], \text{ for fat intake } (i = 2) \text{ upper bound,} \tag{5}$$

$$R_j \leqslant 3, \quad \text{for} \quad j = 1, 2, \ldots, r, \tag{6}$$

$$\sum_{j=1}^{r} S_{kj} R_j = 14, \quad \text{for} \quad k = 1, 2, 3, 4, \tag{7}$$

$$\sum_{j=1}^{r} S_{5j} R_j = 7, \tag{8}$$

$$R_m + R_t + R_c + R_o = 7d, \tag{9}$$

where R_j is an integer variable representing the number of times that the jth recipe will be consumed weekly; C_j is the unit cost of the jth recipe; T_j is the preparation time, waiting time, attentive cooking time, and/or inattentive cooking time required for the jth recipe; r is total number of popular recipes considered; A_{ij} is the amount of the ith nutrient contained in one unit of the jth recipe; N_i is the weekly RDA of the ith nutrient for a predefined group of individuals such as a typical family of four (husband and wife with two children); n is the number of nutrients considered; U_1 is the weekly recommended upper limits for energy intake; S_{kj} is an indicator variable which is set to one if the jth recipe belongs to the kth type (k is 1 for appetizer, 2 for main dish, 3 for side dish, and 4 for dessert) and zero otherwise; S_{5j} is the indicator variable for breakfast recipes (i.e. k is 5); R_m, R_t, R_c, R_o represent the weekly consumption of milk, tea, coffee and fruit or vegetable juice in cups respectively; and d represents the number of individuals in the predefined group.

Equation 1 represents the objective function used to minimize total cost of the selected recipes. Equation 2 represents the objective function used to minimize preparation time, waiting time, attentive cooking time, and/or inattentive cooking time of the selected recipes. Constraint sets 3–9 are used to ensure that the solutions satisfy the recommended nutritional requirements and the predefined course structure. Constraint set 3 ensures that the optimal diet meets the weekly RDA of energy plus eleven selected nutrients for the predefined group of individuals. The eleven selected nutrients are fat, protein, Fe, Ca, Mg, vitamin A and C, pyridoxine, thiamin, folic acid, and riboflavin. Some of these nutrients are considered by nutritionists in Hawaii as limiting (Britten, 1989; Lai *et al.* 1994). It should be noted that the system allows inclusion of other nutrients in addition to those mentioned previously. Constraint set 4 is utilized to avoid excessive intake of energy. U_1 is the recommended upper bound and N_1 is the recommended lower limit for energy intake. In other words, energy intake is constrained to be within the recommended lower and upper bounds (N_1 and U_1). There is no specific RDA for fat intake; however, the (US) National Research Council, Food and Nutrition Board (1989) recommends that fat intake should not exceed 30 % of energy intake. Constraint 5 ensures that fat intake is less than or equal to 30 % of energy intake. The lower bound for fat intake, N_2, is set to zero, that is, fat intake is constrained to be within zero and 30 % of energy intake.

In order to ensure a wider assortment of recipes to minimize the monotony of eating the same food, constraint set 6 is added such that the same recipe cannot be chosen more than three times weekly. We assume this predefined group of individuals will have three meals daily (breakfast, lunch and dinner). Also, each main meal (lunch and dinner) will have an appetizer (soup, salad) dish followed by the main dish with a side dish of vegetables, bread, noodles, or rice, and dessert. These assumptions are represented by constraint set 7. The right-hand side of the constraint set 7 is set to 14 representing the two main meals (lunch and dinner) per d for 1 week while the right-hand side of constraint 8 is set to 7 representing the seven breakfasts for 1 week. It should be noted that each recipe is standardized to d

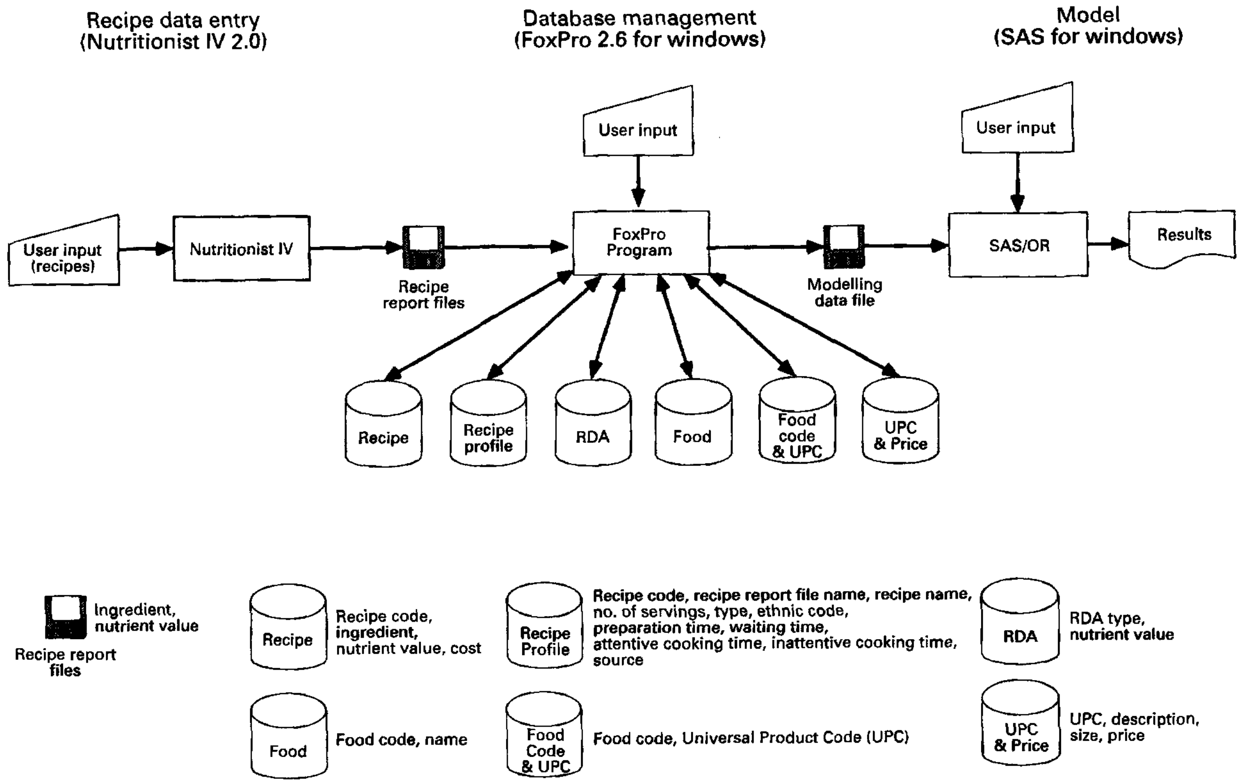

Fig. 1. The computer-assisted modelling system. The programs were: Nutritionist IV 2.0 (Nutritionist IV, 1993), FoxPro 2.6 for windows (Microsoft, 1994), SAS for windows (Statistical Analysis Systems, 1993). RDA, recommended dietary allowance ((US) National Research Council, Food and Nutrition Board, 1989).

servings except for the beverage recipes. The four beverage recipes considered are milk, tea, coffee, and fruit or vegetable juice. Each serving of milk and fruit or vegetable juice contains an 8 oz (237 ml) cup while each serving of the other beverages contains a 6 oz (177 ml) cup. Constraint 9 assumes that each individual in the predefined group consumes one cup of beverage per d.

The computer-assisted modelling system

In order to facilitate the execution of the integer linear programming model, a computer-assisted modelling system has been developed. The modelling system is composed of three separate components (see Fig. 1): recipe data entry, database management, and the model. The recipe data entry component utilizes the *Nutritionist IV® Version 2.0 Diet Analysis* (1993) program for coding and storing recipes. It is also used to generate recipe report files. The recipe report files contain recipe names, computed values of nutrients, food ingredients and serving portions.

The database management component creates and maintains several databases necessary to build the modelling data file for the integer linear-programming model. The program is written in *FoxPro® Version 2.6 for Windows* (Microsoft, 1994). Basically, it reads the recipe report files generated from the Nutritionist IV® (1993) program, computes the total costs for each recipe, captures the preparation time, waiting time, attentive cooking time, and inattentive cooking time for each recipe, captures additional inputs from users such as the profile of the group of individuals to be considered, and writes a special formatted file that can be read by the SAS/OR® program (Statistical Analysis Systems, 1993).

Finally, the model component solves the user-defined integer linear-programming problem using SAS/OR® for windows (Statistical Analysis Systems, 1993).

The modelling system is currently implemented on an IBM-compatible 486 machine. The minimum hardware requirements include an IBM or compatible computer with 80386 CPU or faster, 6 MB or more of RAM, 100 MB of hard disk space, and a dot-matrix printer. The software required to execute the system include: *Nutritionist IV® Version 2.0* (Nutritionist IV, 1993), *Microsoft Windows® Version 3.1* (Microsoft, 1992), *Microsoft FoxPro® for Windows Version 2.6* (Microsoft, 1994) and SAS® and SAS/OR® software products for windows (Statistical Analysis Systems, 1993).

Data sources

The recipe database contains a set of 895 recipes gathered from the Hawaii 4-H youth program collection of popular local recipes, recipes developed by University of Hawaii Cooperative Extension Service, Expanded Food and Nutrition Education Program, and several local and international cookbooks. Prices for the food items necessary to prepare the recipes were provided by a local supermarket chain. Times associated with preparing and cooking a recipe were estimated by a team of people familiar with the particular recipes and were standardized across ethnic types. The daily RDA were taken from the (US) National Research Council, Food and Nutrition Board (1989). It should be noted that RDA represent the minimum nutrient levels to meet the known nutritional needs of most healthy persons. The RDA have been considered as the safest standards because nutrient needs of individuals vary and there is no way of predicting the needs of a specific individual. One cup of low-fat (2%) milk is included with all cereals listed for breakfast.

RESULTS

The model was applied to generate diet plans for a family of four for 1 week by minimizing total cost, preparation time, attentive cooking time, preparation and attentive cooking time, and total time respectively. Total time includes preparation, waiting, attentive and inattentive cooking time. For the present study the model was run as a single-objective

Table 1. *The payoff matrix representing the degree of conflict among the various objectives under consideration in the recipe-based diet-planning modelling system*

Objectives	Total cost (US$/week)	Preparation time (min/week)	Attentive cooking time (min/week)	Preparation and attentive cooking time (min/week)	Total time (min/week)
Total cost	**71·13***	1320	360	1680	5545
Preparation time	207·99	**279***	565	844	2059
Attentive cooking time	77·01	1528	**0***	1528	5917
Preparation and attentive cooking time	181·86	410	108	**518***	1924
Total time	159·47	515	169	684	**710***

* Ideal point, i.e. the solution where all the objectives reach their optimum value.

integer programming problem separately for each of the time objectives and cost. This typical family of four is assumed to have a couple between age 25 and 50 years with two children between age 7 and 10 years. Their combined weekly RDA for energy plus the eleven selected nutrients were used.

Table 1 shows the payoff matrix representing the degree of conflict among the various objectives under consideration. Each row represents the effects of minimizing the respective objective on the other objectives. For example, row 1 shows the values of each objective when total cost is minimized. Total cost is minimized at $71·13 for the typical family of four for 1 week. However, this typical family will have to spend 1320 min of preparation time, 360 min of cooking time, and a total of 5545 min of total time in this 1 week. The elements of the main diagonal in the payoff matrix (see Table 1) are referred to as the 'ideal point', that is, the solution where all the objectives achieve their optimum value. There is a clear conflict among the cost and the various time objectives in our case and this 'ideal solution' is infeasible. For example, when total time is minimized at 710 min per week, total cost has to increase to $159·47, more than twice as much as the least-cost solution. Total weekly cost has to increase even more when preparation and attentive cooking time are minimized together.

Since the most critical time involved in preparing a meal is the preparation and attentive cooking time, detailed solutions are presented only for this case and compared with the least-cost solution. The other solutions using different objectives are detailed in Quinn *et al.* (1995). Tables 2 and 3 show respectively the least-cost and the least-preparation and attentive cooking time (least-time) weekly diet plans for the typical family of four.

Obviously, the least-cost diet plan selects less costly recipes to satisfy the RDA regardless of time while the least-time diet plan selects the less time-consuming recipes regardless of cost. The least-cost diet plan relies mainly on starch-based foods to satisfy the nutritional needs of the family. In fact, most of the recipes chosen are baked goods which are more time-consuming with respect to preparation time. The most drastic difference is in the dessert category where all the chosen recipes are baked goods in the least-cost diet plan while the least-time diet plan contains all fresh fruits. This shows a clear trade-off between cost and time where baked goods are generally less expensive but more time-consuming to prepare and vice versa for fresh fruits. The side dish category also shows a clear choice of less expensive, but more time-consuming baked goods primarily bread for the least-cost plan. The least-time solution provides a wider selection of vegetable dishes in the side dish category. Fortified cereals are chosen for both diet plans. There are fewer servings of cereals in the least-cost plan, but more highly fortified products are chosen.

Table 2. *Least-cost weekly diet plan for an Hawaiian family of four developed using a recipe-based diet-planning modelling system*

Recipes	Quantity (unit)*	Unit cost (US$/unit)	Total cost (US$/week)	Preparation time (min/week)	Attentive cooking time (min/week)	Preparation and attentive cooking time (min/week)	Total time (min/week)
Appetizer							
Ogu namasu (pickled seaweed)	1	0·87	0·87	20	0	20	20
Green papaya salad	3	0·83	2·49	60	0	60	60
Guacamole in cherry tomatoes	1	0·91	0·91	25	0	25	25
Chicken liver broil	3	0·98	2·94	15	45	60	240
Chinese cabbage soup	3	0·90	2·70	45	15	60	135
Baked tomatoes	3	0·77	2·31	60	0	60	135
Main dish							
Squid guisado	3	1·49	4·47	75	75	150	180
Egg salad sandwich	3	1·29	3·87	45	0	45	60
Banana ham patties	3	1·81	5·43	60	15	75	90
Pasta with potato and cheese	3	2·29	6·87	30	45	75	75
Noodles with pork and water chestnuts	2	2·24	4·48	24	20	44	60
Side dish							
Parmesan rolls	1	1·44	1·44	15	0	15	17
Steamed bread	1	1·05	1·05	30	0	30	160
Sweet and sour carrots	3	0·66	1·98	15	30	45	45
Freezer french bread	3	0·91	2·73	90	0	90	1605
Mary's No Knead french bread	3	0·40	1·20	90	0	90	495
Oatmeal bread	3	0·62	1·86	75	0	75	960
Dessert							
Brown-edge lemon wafers	3	0·45	1·35	135	0	135	165
Caraway cake	3	0·36	1·08	135	0	135	156
Lavosh	3	0·61	1·83	60	0	60	96
Baked mochi	3	0·46	1·38	45	0	45	180
Gau	2	0·64	1·28	30	0	30	150
Breakfast							
Grandma's Andagi	1	1·37	1·37	20	25	45	45
Grape nuts cereal	1	1·88	1·88	1	0	1	1
100% Bran cereal	1	2·08	2·08	1	0	1	1
Product 19 cereal	1	2·52	2·52	1	0	1	1
Malasadas (Portuguese doughnuts)	3	0·49	1·47	90	90	180	360
Beverages							
Non-fat milk	27	0·26	7·02	27	0	27	27
Low-fat (2%) milk	1	0·27	0·27	1	0	1	1
Total			71·13	1320	360	1680	5545

* One unit represents four servings except for beverages which are in cups (8 oz (237 ml) cup for milk and fruit or vegetable juice, 6 oz (177 ml) cup for other beverages).

Table 3. *Least-preparation and attentive cooking time weekly diet plan for an Hawaiian family of four developed using a recipe-based diet-planning modelling system*

Recipes	Quantity (unit)*	Unit cost (US$/ unit)	Total cost (US$/ week)	Preparation time (min/ week)	Attentive cooking time (min/ week)	Preparation and attentive cooking time (min/ week)	Total time (min/ week)
Appetizer							
Cucumber–chicken cup	3	1·85	5·55	24	15	39	39
Hot Senegalese soup	3	1·54	4·62	15	24	39	39
Tofu poke	3	3·50	10·50	30	0	30	120
Mushroom soup	2	2·58	5·16	16	10	26	156
Bamboo shoot soup	3	3·69	11·07	15	15	30	75
Main dish							
Barbecue chicken	3	3·72	11·16	30	0	30	150
Orange chicken	3	3·44	10·32	24	0	24	174
No-fat fry with onions	3	3·01	9·03	30	0	30	180
Peachy low-calories chicken	2	6·28	12·56	20	0	20	150
Chicken breast piquant	3	5·02	15·06	24	0	24	294
Side dish							
Parmesan rolls	3	1·44	4·32	45	0	45	51
Savoury oven vegetables	3	1·26	3·78	30	0	30	120
Baked beans with portuguese sausage	3	2·44	7·32	30	0	30	240
Sweet and sour carrots	2	0·66	1·32	10	20	30	30
Mushroom and cauliflower	3	2·31	6·93	15	24	39	54
Dessert							
Banana	3	1·00	3·00	3	0	3	3
Mango haden	3	3·00	9·00	6	0	6	6
Pear-bartlet	2	2·20	4·40	2	0	2	2
Pear-d'anjou	3	2·64	7·92	3	0	3	3
Persimmons	3	3·40	10·20	3	0	3	3
Breakfast							
Crispy rice cereal	1	2·00	2·00	1	0	1	1
Life-plain/cinnamon cereal	3	2·20	6·60	3	0	3	3
Toasties cereal	3	1·92	5·76	3	0	3	3
Beverages							
Prune juice	28	0·51	14·28	28	0	28	28
Total	—	—	181·86	410	108	518	1924

* One unit represents four servings except for beverages which are in cups (8 oz (237 ml) cup for milk and fruit or vegetable juices, 6 oz (177 ml) cup for other beverages).

Table 4 compares the nutrients provided by the two diet plans. By design, both plans provide sufficient nutrients for the family as defined in the RDA. The least-cost plan provides more energy than the least-time plan. However, energy intake is on the low side (i.e. closer to the lower limit of RDA) and fat intake is on the high side (i.e. closer to 30% of energy intake) for both plans. The least-cost plan barely covers the recommended levels of Ca, Mg and pyridoxine but it provides plentiful amount of the other nutrients. The least-time plan provides more than ample amount of all nutrients except for Ca which is barely met. However, it provides smaller amounts of vitamins A, thiamin, folic acid, and riboflavin than the least-cost plan.

Table 4. *Amount of nutrients provided by the least-cost and least-preparation and attentive cooking time weekly diet plans for an Hawaiian family of four developed using a recipe-based diet-planning modelling system*

			Least cost plan		Least-preparation and attentive cooking time plan	
Nutrients	Unit	RDA	Amount provided	Percentage of RDA met	Amount provided	Percentage of RDA met
Energy*	kJ	213217–319825	213242	100	222785	104
	kcal	50960–76440	50966		53247	
Fat†	g	≤ 30% of energy	1696	30	1774	30
Protein	g	1183	1936	164	3292	278
Iron	mg	315	482	153	660	210
Calcium	mg	22400	22427	100	22406	100
Magnesium	mg	6790	6823	100	8881	131
Vitamin A	RE	22400	69397	310	66481	297
Vitamin C	mg	1470	2093	142	2721	185
Thiamin	mg	32·2	62·9	195	40·4	125
Pyridoxine	mg	44·8	44·8	100	83·5	186
Folic acid	μg	4060	12055	297	6086	150
Riboflavin	mg	37·8	85·6	226	64·8	171

RDA, recommended dietary allowance ((US) National Research Council, Food and Nutrition Board, 1989); RE, retinol equivalent.

* For energy percentage met is the percentage of lower bound (see pp. 152–153).

† For fat, percentage met is the percentage of energy intake which is constrained to be less than or equal to 30%.

Table 5 compares the nutrient contribution, cost and time distributions by meal category for the two diet plans. The distribution of cost among the meal categories is very similar for the two diet plans with the largest share about 32–35% attributed to the main dishes. This is followed by appetizers (17–20%), side dishes (13–14%), desserts (10–19%), breakfasts (8–13%), and beverages (8–10%). However, while the time for the least-cost plan is more evenly distributed among the meal category except for beverages, the bulk of the time (91%) for the least-time plan is attributed to preparing appetizers, main dishes, and side dishes. The major difference can be attributed to the dessert and breakfast categories where the least-cost plan uses many time consuming, less expensive baked products whereas the least-time plan uses all fruits for dessert and cereal products for breakfast.

Main dishes provide about 44 and 57% of the protein for least-cost and least-time plans, respectively. Together with the side dishes they provide most of the energy and fat in both plans. The main dishes and side dishes together provide the major share of most of the nutrients. Appetizers account for a larger contribution for most nutrients in the least-time plan except for vitamins A and C and pyridoxine and folic acid. The dessert category in the least-cost plan which contains predominantly starch-based recipes provides more energy, fat and protein than the least-time plan which contains all fruits. Except for a significant amount of vitamin A (46%) and vitamin C (38%), and a fair amount of Mg, pyridoxine and riboflavin in the least-time plan, desserts do not provide as many vitamins and minerals in either plan as the other categories. Breakfasts provide a consistent and significant supply of all nutrients in both plans despite the fact that there are only seven breakfasts but fourteen lunches and dinners in 1 week. The beverage category generally provides less than

Table 5. *Nutrient composition (%), cost and time distributions by meal category for the least-cost and least-preparation and attentive cooking time diet plans for an Hawaiian family of four developed using a recipe-based, diet-planning modelling system*

	Least-cost plan						Least-preparation and attentive cooking time plan					
Nutrient	Appetizer	Main dish	Side dish	Dessert	Breakfast	Beverage	Appetizer	Main dish	Side dish	Dessert	Breakfast	Beverage
Energy	7	32	22	19	16	5	15	28	21	13	12	10
Fat	11	38	13	19	18	1	29	34	28	1	8	0
Protein	10	44	15	7	12	12	19	57	10	2	10	1
Iron	13	27	22	13	25	1	35	15	17	4	16	13
Calcium	6	20	7	9	20	38	29	7	13	4	43	4
Magnesium	11	31	19	8	18	12	26	22	13	14	13	11
Vitamin A	33	4	40	2	15	6	5	3	33	46	13	0
Vitamin C	52	21	5	1	18	3	15	14	19	38	3	11
Thiamin	6	39	21	7	22	4	16	13	22	9	37	3
Pyridoxine	17	28	10	4	35	6	8	36	9	16	12	19
Folic acid	38	12	22	3	22	3	17	13	25	13	30	0
Riboflavin	12	38	11	4	24	11	16	19	12	9	37	8
Cost	17	35	14	10	13	10	20	32	13	19	8	8
Time	17	23	21	24	14	2	32	25	34	3	1	5

15% for most nutrients except for Ca which accounts for 38% in the least-cost plan and pyridoxine which accounts for 19% in the least-time plan.

DISCUSSION

As expected, the present study provides a nutritionally adequate diet at a smaller cost than the previous pilot study by Leung *et al.* (1992), \$71·13 *v.* \$80·03 per week for the hypothetical family of four. This lower cost can be explained by the fact that the present study uses a much larger set of recipes, 895 *v.* 217 in the pilot study.

In comparison with the least-cost diet plan generated without the recipe constraint, i.e. optimizing over food items instead of optimizing over recipes, the weekly cost is about 2·9 times higher, \$71·13 *v.* \$24·09. The least-cost diet plan without the recipe constraint is obtained using the same set of food items necessary for the 895 recipes. Similar to most previous studies, this diet plan suggests a surprisingly low cost of satisfying the purely nutritional needs. However, this diet plan is not likely to be widely adopted as most people would find it rather unappetizing or difficult to convert the selected food items into palatable meals. As expected, only a few food items will be selected for this diet. They are beef liver, papaya, long-grain white rice, stirred whole-grain wheat flour, all-purpose white wheat four, Kellogg's cereal product 19 and table salt.

The study extends the previous pilot study by including various time objectives other than minimizing cost. The results from minimizing the various time objectives demonstrate a clear trade-off between cost and time by selecting appropriate recipes which achieve the respective objectives and at the same time satisfy the minimum nutritional requirements. In order to save time, the cost of the least-time diet plan is estimated to cost \$181·86 per week for the family of four, an increase of \$110·73 compared with the least-cost plan of \$71·13. However, the least-time plan saves about 1162 min per week, or a saving of about 19 h.

This translates to about \$5·70 per h, not an insignificant amount. Of course, there are possibly many diet plans somewhere between the least-cost plan and the least-time plan which may suit individual preferences with respect to the optimal combination of cost and time. In the present paper, only the two extreme diet plans are presented to illustrate the potential use of the modelling system. The authors have recently employed a two-criteria generating method with the modelling system to trace the efficient frontier of diet plans with different combinations of cost and time (P. S. Leung, W. Miklius, K. Wanitprapha & L. A. Quinn, unpublished results). Other multiple-criteria methods such as the various forms of goal programming can also be readily implemented using the modelling system. An example would be a formulation of a weighted-goal programming model with the user specifying the weights of the two goals of minimizing time and minimizing cost.

The recipe-based diet planning modelling system presented in the present paper provides an efficient means to generate palatable diets with differing objectives. The system is developed with an open architecture in two major aspects. First, it allows addition and deletion of recipes into and out of the system. Secondly, models with different objectives and/or constraints can be specified and subsequently executed. The system can be easily adapted for other countries, regions or localities to generate nutritionally sufficient and palatable diets by using region-specific recipes. Such a system can serve as a useful decision aid in the nutrition intervention process.

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