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Use of Linear Programming to Develop Cost-Minimized Nutritionally Adequate Health Promoting Food Baskets

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Abstract

Background

Food-Based Dietary Guidelines (FBDGs) are developed to promote healthier eating patterns, but increasing food prices may make healthy eating less affordable. The aim of this study was to design a range of cost-minimized nutritionally adequate health-promoting food baskets (FBs) that help prevent both micronutrient inadequacy and diet-related non-communicable diseases at lowest cost.

Methods

Average prices for 312 foods were collected within the Greater Copenhagen area. The cost and nutrient content of five different cost-minimized FBs for a family of four were calculated per day using linear programming. The FBs were defined using five different constraints: cultural acceptability (CA), or dietary guidelines (DG), or nutrient recommendations (N), or cultural acceptability and nutrient recommendations (CAN), or dietary guidelines and nutrient recommendations (DGN). The variety and number of foods in each of the resulting five baskets was increased through limiting the relative share of individual foods.

Results

The one-day version of N contained only 12 foods at the minimum cost of DKK 27 (€ 3.6). The CA, DG, and DGN were about twice of this and the CAN cost ~DKK 81 (€ 10.8). The baskets with the greater variety of foods contained from 70 (CAN) to 134 (DGN) foods and cost between DKK 60 (€ 8.1, N) and DKK 125 (€ 16.8, DGN). Ensuring that the food
baskets cover both dietary guidelines and nutrient recommendations doubled the cost while cultural acceptability (CAN) tripled it.

**Conclusion**

Use of linear programming facilitates the generation of low-cost food baskets that are nutritionally adequate, health promoting, and culturally acceptable.

**Introduction**

In OECD countries micronutrient inadequacy can co-exist with excess calorie intake [1,2]. Vulnerable groups, especially pregnant women within low socio-economic groups and their families are at high risk [3,4]. Evidence suggests that increased intake of micronutrient-dense foods with low energy density can help to prevent nutrition-related noncommunicable diseases (NCD) along with micronutrient inadequacies [5] and corresponding national food-based dietary guidelines (FBDGs) have been developed in many countries [6]. However, micronutrient-dense foods are relatively expensive [7] so people, especially those on low incomes, buy less and this increases risk of micronutrient inadequacies [8]. Even in high-income countries, economic constraints and actual lifestyles lead people to consume diets with a low micronutrient-energy ratio [9]. Both micronutrient inadequacy and excess weight gain is expected to increase along with inequalities during economic crises even in high-income countries [10].

NCDs are the primary cause of premature morbidity in Europe [11,12]. EU and WHO Member States have called for action to prevent both NCDs and micronutrient deficiency through improved dietary practices [13,14]. There are many drivers of food purchase but the most important are: taste, availability/access, habit, and cost [15]. Governments have tried to provide positive, easy-to-understand, and readily affordable dietary guidelines in order to change population eating patterns to reduce the increasing prevalence of inequality in diet-related NCDs [1,16,17]. However the introduction of national FBDGs appears not to reduce prevalence of dietary related NCDs especially in low income groups [18].

There is a need for mathematical modelling to help calculate which foods can supply the optimum nutrient recommendations for low cost, especially for income strapped households and authorities e.g. catering services within the public sector. The method of LP has been used to optimise the average daily nutrient intake, for children and adults since the nineteen-fifties [19–22]. Several non-EU governments use LP methodology to estimate how much money their national population need to cover the cost of a nutritionally adequate diet e.g. Canada [23], Australia [24], and the United States [25]. However within Europe similar methods do not appear to be used e.g. to help governments plan their social and welfare policies.

The main aim of this study was to use linear programming methodology to design a range of cost-minimised health-promoting food baskets (FBs) that could both help to prevent micronutrient inadequacies and to be culturally acceptable for a low-income family. Five one day (24hr) low-cost FBs for a family of four were defined using five different constraints: cultural acceptability (CA) [26]; dietary guidelines (DG) [27]; nutrient recommendations (N) [6]; cultural acceptability; and nutritional adequacy (CAN), or dietary guidelines and nutrient recommendations (DGN). Realistically, family households and public catering services cannot provide the same menu to consumers day after day. In addition, the lack of variety in diets is associated with poor nutritional adequacy [28] and poor health status [29]. Hence, this study also aims to investigate how food variety within the FBs affects cost and micronutrient content.
and which micronutrient recommendations influence the overall cost of a healthy diet the most.

**Materials and Methods**

**Generation of the list of foods usually available in Greater Copenhagen**

A list of 312 unprocessed or minimally processed foods was generated. These were grouped into categories similar to 13 out of 14 food categories used in the Danish food consumption survey (Table 1) [26]. Ready meals and beverages were not included. Particular care was taken to include foods rich in vitamin D (i.e. cod liver, cod liver oil, and cod roe) due to challenges to meet vitamin D recommendations [30].

**Food prices**

The collection of food data, including prices, was carried out within the Greater Copenhagen area (S1 Table). The price of each food was collected in five discount retailers (Netto, Rema 1000, Aldi, Lidl, and Fakta) along with two online retailers (Nemlig.com and Superbest.com) between March and December 2014. All shop managers gave their informed consent.

### Table 1. Food groups and subgroups of foods with examples of foods included in the analysis.

| Food group [26] | Subgroups with examples | Number of food items |
|-----------------|-------------------------|----------------------|
| Milk and milk products | Milk with varying fat content, cream, sour-fermented milk products (yoghurt, kefir etc.) | 16 |
| Cheese and cheese products | Hard and soft cheese, cottage cheese, curd | 15 |
| Cereals and other starchy foods | Bread, flour, pasta, rice, oats, bulgur, quinoa, muesli | 35 |
| Potatoes | Potatoes fresh and frozen (wedges, chips), potato products (potato flour, instant potato flakes) | 8 |
| Vegetables | Leafy vegetables (cabbage, leeks, lettuce, spinach etc.) | 15 |
| | Non-leafy vegetables (tomatoes, green pepper, cucumber, broccoli, cauliflower etc.), snap beans, ketchup | 21 |
| | Root vegetables (onions, carrots, beetroot, Jerusalem artichoke, parsnip, celeriac etc.) | 13 |
| | Pulses including lentils, peas, beans, and chickpeas | 16 |
| | Mushrooms | 5 |
| Fruits, nuts and seeds | Fruits (including dried fruits) | 41 |
| | Nuts and seeds, olives | 21 |
| Juices | Apple juice, orange juice, etc. | 3 |
| Meat and meat products | Unprocessed (pork, beef, lamb) and moderately processed meat (sausage, salami etc.) | 27 |
| | Offal (liver, heart, kidneys) from pork, beef, and veal | 8 |
| Poultry | Chicken, turkey, goose, duck, chicken liver/heart and products | 16 |
| Fish and fish products | Seawater (cod, plaice, tuna, salmon) and freshwater (trout) fish, cod liver, and cod roe | 21 |
| Eggs | Eggs | 1 |
| Fats and oils | Plant oils (rapeseed, sunflower, olive), butter, margarine, coconut fat, cod liver oil, mayonnaise | 14 |
| Sugar, honey, and sweets | Sugar, honey, chocolate, chocolate bars and spread, syrup etc. | 13 |
| Condiments | Salt, vinegar | 3 |

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consent to the collection of food prices. The lowest price was selected if one food cost a range of different prices at time of data collection. The price per kilogram of edible food was calculated in Danish Kroner (DKK) per kilogram (kg). To correct for different nutrient composition between cooked and unprepared foods, two factors were adjusted: the change in water content during preparation (before–after preparation); and the loss of pecuniary value due to cost of non-edible parts (waste such as shells, peel, skins, fruit stones, bones etc.) [31,32]. To adjust for these two factors, the following formula (1) was applied:

\[
\text{Price}_{\text{Edible food}} = \frac{\text{Price}_{\text{Raw food}}}{(100\% - \% \text{Water Content in prepared food}) \times 100\% \times \% \text{Edible portion}}
\]

If food was sold per item, 4–6 items were weighed on-site and the average weight (kg) was used to calculate the price. For the calculation of price per kg from online shops, standard weights for fruits and vegetables were used [33].

**Food Composition Tables**

The Danish (Foodcomp) [31] or, where necessary, the American (SR28) [32] food composition tables and databases were used to obtain food composition values. Where appropriate, the values for prepared (cooked, baked, simmered, etc.) foods were used. Values for the average edible weight of each food were obtained from the same food composition tables and databases [31,32].

**Linear programming**

Linear programming (LP) is an algorithm for maximising or minimising a given (linear) objective function subject to a set of linear constraints [34] on a list of decision variables. The decision variables were whether a food was selected and at what weight. The objective function minimized the total cost of the FB (the sum of the cost of each food in the basket). Each food was characterised by its price and its nutrient content. LP was used to design five different FBs, which were defined using the following sets of constraints (Table 2):

1. Culturally acceptable FB (CA) follows current eating patterns in Denmark [26];
2. Health-promoting FB (DG)—follows the Danish food-based dietary guidelines [27];
3. Nutritionally adequate FB (N)—meets all recommended Nordic nutrient intake values [6];
4. Culturally acceptable, nutritionally adequate FB (CAN)—both culturally acceptable and nutritionally adequate i.e. combines (i) CA and (iii) N;
5. Both health-promoting and nutritionally adequate FB (DGN)—i.e. combines (ii) DG and (iii) N;

In all cases, the goal was to minimize the cost of the FBs. The LP algorithm used is available as an MS Excel® open-source add-in (OpenSolver) [35], where the “COIN Branch and Cut” option was used to ensure the implementation of all constraints for each of the five different FBs. The nutrient recommendations [6] were applied individually to each member of a family of four: woman, aged 31–50 years; man, aged 31–50 years, one girl aged 4 years, and one boy aged 8 years (Table 2). This family combination was selected as it represents the household most commonly found in Denmark [36]. A daily FB was calculated for each family member and then merged to give a household’s FB for one day. All five different FBs provided the average daily age- and gender-adjusted energy intake (per individual) as recommended by the Nordic recommendations [6] (Table 2). All LP constraints for each FB are listed in Table 2.
Table 2. Constraints applied to the five food baskets (FBs): (i) culturally acceptable FB (CA) i.e. follows current consumption of 13 food categories in Denmark [26]; (ii) nutritionally adequate FB (N) i.e. meets all nutrient recommendations [6]; (iii) health promoting FB (DG) i.e. follows national food-based dietary guidelines [27], (iv) both nutritionally adequate and health-promoting FB (DGN) i.e. combines (ii) and (iii), and both nutritionally adequate and culturally acceptable (CAN) i.e. combines (i) and (ii). When ranges are given, both the upper and lower limits were applied as LP constraints. EI: energy intake; app.: applied; AC: average consumption.

|                | Girl | Boy | Female | Male | CA  | DG  | N    | CAN  | DGN  |
|----------------|------|-----|--------|------|-----|-----|------|------|------|
| Age (y)        | 4    | 8   | 31–60  | 31–60|      |     |      |      |      |
| Energy Kcal/day (MJ/day) | 1403 (5.87) | 1738 (7.27) | 2103 (8.80) | 2629 (11.0) | app. | app. | app. | app. | app. |
| AC of milk (products) (g/day) | 398 | 457 | 273 | 337 | app. | -   | -    | app.  | -    |
| AC of cheese (g/day) | 21  | 20  | 41  | 47  | app. | -   | -    | app.  | -    |
| AC of bread + cereals (g/day) | 204 | 228 | 189 | 249 | app. | -   | -    | app.  | -    |
| AC of potato (products) (g/day) | 38 | 42 | 65 | 118 | app. | -   | -    | -    | app.  |
| AC of vegetable + pulses (g/day) | 157 | 158 | 206 | 191 | app. | -   | -    | app.  | -    |
| AC of fruit (products) (g/day) | 183 | 192 | 212 | 166 | app. | -   | -    | app.  | -    |
| AC of juice (mL) | 60  | 57  | 54  | 59  | app. | -   | -    | app.  | -    |
| AC of meat + offal (g/day) | 82  | 91  | 99  | 172 | app. | -   | -    | app.  | -    |
| AC of poultry (g/day) | 14  | 18  | 24  | 29  | app. | -   | -    | app.  | -    |
| AC of fish (products) (g/day) | 15  | 17  | 34  | 40  | app. | -   | -    | app.  | -    |
| AC of eggs (g/day) | 17  | 19  | 23  | 26  | app. | -   | -    | app.  | -    |
| AC of fats + oils (g/day) | 35  | 39  | 35  | 47  | app. | -   | -    | app.  | -    |
| AC of sweets + chocolate (g/day) | 33  | 36  | 35  | 38  | app. | -   | -    | app.  | -    |

Milk (products)  
- Milk with <0.7% fat only, fermented milk products <1.5% fat, daily consumption 250–500 mL; cheese with <17% fat only  
Starchy foods  
- >75 g (children: 50/62 g) of whole grain products, >250/300 g (children: 167/207 g) of starchy foods  
Ratio of food categories  
- Ratios of sum amounts of meat, poultry, fish, eggs, cheese: vegetable + fruit: potatoes + whole grain products = 1:2:2  
Vegetables + fruits  
- >600 g (children: 200/248 g) vegetable + fruits, min. ½ of which is vegetable and max. 100 mL juice  
Meat  
- No meat with >10% fat; red meat <500 g/week (children: 336/413 g/week)  
Fish  
- >350 g total (children: 231/287 g); >200 g fatty fish (children: 133/168 g)  
Animal fats  
- Not allowed  
Sugar + sweets  
- To be minimized  
Proteins (% of total EI)  
- 10–20  
Lipids (% of total EI)  
- 25–40  
SFA (% of total EI)  
- <10  
MUFA (% of total EI)  
- 10–20  
PUFA (% of total EI)  
- 5–10  
w-3 FA (% of total EI)  
- >1  
Trans-FA (% of total EI)  
- <1  
Carbohydrates (% of total EI)  
- 45–60  
Sugar (% of total EI)  
- <10  
Fibre (g/MJ)  
- >2  
Sodium (mg)  
- <1440  
Potassium (mg)  
- >1800  
Calcium (mg)  
- 600–2500  
Magnesium (mg)  
- >120  
Iron (mg)  
- 8–25  
Zinc (mg)  
- 6–25  
Copper (mg)  
- 0.4–5  

(Continued)
A food basket was considered the more culturally acceptable the less it deviated from the eating pattern of the Danish population [8]. The 312 foods, with Danish prices collected, were grouped into the same categories as those used in Danish food intake survey 2011–2013 [26]. The maximum relative deviation (MRD) for each food category was calculated as the difference between the total weight of food in basket minus the average weight consumed and divided by the average weight consumed within the same category [Formula (2)].

\[
MRD = \frac{\text{abs}[\sum_{i}^{n} m_i - m_i(\text{av})]}{m_i(\text{av})}
\]  

In formula (2), the following abbreviations were used: \(n\): number of foods in j-th food category; \(m_i(\text{av})\): average weight of foods consumed in j-th category. In food basket CA, the total weight of foods in each category was matched to correspond to the average age- and sex-specific amount consumed by the Danish population (MRD = 0) [26]. The categories and the corresponding values for \(m_i(\text{av})\) of each family member are listed in Table 2. In this table, the combination of constraints for each FB is indicated in one of the five columns to the right.

(ii) Health-promoting food basket (DG) and constraints enforced using LP. Food basket DG was calculated using LP to enforce the Danish food-based dietary guidelines (FBDGs) along with the appropriate ratios of food categories as recommended by the Ministry of Food, Agriculture and Fisheries of Denmark [27]. The constraints from the guidelines are listed in Table 2. For the children in the family, the absolute amounts of fish, fruits and vegetables, whole-grain products and meat were adapted proportionally to their individual energy recommendations (Table 2).

(iii) Nutritionally adequate food basket (N) and constraints enforced using LP. Food basket N was calculated using LP to enforce the Nordic recommended nutrient intake values [6] as constraints. The recommended values for macronutrients, fibre, and minerals/micronutrients (sodium, potassium, calcium, magnesium, iron, zinc, selenium, iodine, phosphorus, thiamine, riboflavin, niacin, folate, and the vitamins C, B6, A, E, D, and B12) [6] were calculated according to each individual’s energy recommendation (Table 2).

(iv) Nutritionally adequate and health-promoting food basket’s (DGN) constraints enforced using LP. The DGN food basket was calculated using LP to enforce a combination

Table 2. (Continued)

|                | Girl | Boy  | Female | Male  | CA | DG | N   | CAN | DGN |
|----------------|------|------|--------|-------|----|----|-----|-----|-----|
| Selenium (μg)  | 25–300 | 30–300 | 50–300 | 60–300 | -  | -  | app.| app.| app.|
| Phosphorus (mg)| 470–3000 | 540–3000 | 600–3000 | 600–3000 | -  | -  | app.| app.| app.|
| Iodine (μg)    | 90–600  | 120–600  | 150–600  | 150–600  | -  | -  | app.| app.| app.|
| Vit A (RAE)    | >350 | >400 | >700 | >900 | -  | -  | app.| app.| app.|
| Thiamin (mg)   | >0.6 | >0.9 | >1.1 | >1.3 | -  | -  | app.| app.| app.|
| Riboflavin (mg)| >0.7 | >1.1 | >1.2 | >1.5 | -  | -  | app.| app.| app.|
| Vit B6 (mg)    | 0.7–25 | 1–25 | 1.2–25 | 1.5–25 | -  | -  | app.| app.| app.|
| Vit B12 (μg)  | >0.8 | >1.3 | >2   | >2   | -  | -  | app.| app.| app.|
| Vit C (mg)     | 30–1000 | 40–1000 | 75–1000 | 75–1000 | -  | -  | app.| app.| app.|
| Vit D (μg)     | 10–100 | 10–100 | 10–100 | 10–100 | -  | -  | app.| app.| app.|
| Vit E (mg)     | 5–300 | 6–300 | 8–300 | 10–300 | -  | -  | app.| app.| app.|
| Folate (μg)    | 80–1000 | 130–1000 | 300–1000 | 300–1000 | -  | -  | app.| app.| app.|
| Niacin (mg)    | 9–900 | 12–900 | 14–900 | 18–900 | -  | -  | app.| app.| app.|

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of both (ii) DG and (iii) N so that the DGN is both nutritionally adequate \[6\] and follows the Danish food-based dietary guidelines. For details, see Table 2.

(v) Nutritionally adequate and culturally acceptable food basket’s (CAN) constraints enforced using LP. The CAN food basket was calculated using LP to enforce a combination of both (i) CA and (iii) N so that the CAN is both culturally acceptable \[26\] and nutritionally adequate \[6\]. For details, see Table 2.

Computation of shadow prices for single micronutrients in N

In LP models, constraints that are influencing the lowest cost (the objective function) are called “active constraints”. These consider the constraint that micronutrient levels must be equal to 100% of their recommended intake value. The shadow cost of a nutrient is calculated by the difference in the objective function value (the lowest cost) with and without an active constraint \[37\]. So that for each active constraint, its shadow cost was estimated by calculating the difference in cost between the FB with, and without, that constraint. After the nutrients with high shadow cost were identified, the foods rich in those nutrients were tested to examine how overall cost is influenced by their inclusion.

Increased diversity (using a greater number and variety of foods) was modelled in all FBs through a step-wise reduction of the relative amount of foods within each category

Food baskets based on one day’s recommendations consist of a small number (6–12) of foods \[19\]. Such a restricted number of foods would be monotonous and unrealistic on a regular daily basis. Therefore in order to increase variation, the proportion of a food within a category, was limited using a systematic process where: 200%, 150%, 100%, 70%, 50%, 40%, 30%, 20%, and 10% of the average weight \[m_j(\text{av})\] according to the Danish dietary intake survey was calculated. For example: for an adult female the average consumption of milk and milk products was 273 g per day (Table 2); therefore in order to increase the number of foods within “milk products”, the proportion of the food was reduced in a step-wise process from 546 g (200%) to 27.3 g (10%). The FB was systematically re-calculated according to the minimum cost. The resulting cost, of approx. 100 foods, was calculated for 30.5 days or equivalent to a one-month’s family food basket.

The deviation from the usual Danish eating pattern was calculated as the average relative deviation (ARD) from average food consumption \[26\] (Formula (3)):

$$\text{ARD} = \frac{1}{13} \sum_{j=1}^{13} \left\{ \frac{\text{abs} \left[ \frac{\sum_{i=1}^{n} m_{ij} - m_j(\text{av})}{m_j(\text{av})} \right]}{m_j(\text{av})} \right\}$$  \(3\)

In Formula (3), \(m_{ij}\) indicates the i-th food in the j-th food category. All other abbreviations are same as in Formula (2).

Results

The least expensive food baskets, containing from 6 (DG) to 33 (CAN) foods, cost from ~DKK 24 (€ 3.2, N) to ~DKK 80 (€ 10.8, CAN) (Table 3). Combination of both nutrient and dietary recommendations (DGN) more than doubled the cost compared to N and making N culturally acceptable (CAN) more than tripled its cost (Table 3).

The RIs of vitamins D, C, calcium, iodine, potassium, and riboflavin were active constraints and controlled the total cost of basket N. These micronutrients accounted for shadow prices of 10%, 9%, 5%, 3%, 3%, and 2%, respectively. Achieving the lowest cost depended on the
Table 3. Simplest and most affordable one-day food baskets (CA, DG, N, DGN, CAN) that follow the constraints listed in Table 2.

| Food Item               | CA Weight (g) | Cost (DKK) | DG Weight (g) | Cost (DKK) | N Weight (g) | Cost (DKK) | DGN Weight (g) | Cost (DKK) | CAN Weight (g) | Cost (DKK) |
|-------------------------|---------------|------------|---------------|------------|--------------|------------|----------------|------------|----------------|------------|
| Milk, skimmed           | 1466          | 7.25       | 873           | 4.32       | 303          | 1.50       | 873            | 4.32       |                |            |
| Milk, 0.5%              | 101           | 0.50       |               |            |              |            |                |            |                |            |
| Milk, 3.5%              |               |            |               |            |              |            | 1364           | 8.11       |                |            |
| Cheddar, 33%            | 100           | 3.28       |               |            |              |            |                |            |                |            |
| Curd, 1%                | 29            | 0.87       |               |            |              |            |                |            |                |            |
| Soy drink, 2.2%         |               |            |               |            |              |            | 620            | 11.75      |                |            |
| Rice, parboiled         | 646           | 1.80       | 361           | 1.01       |              |            | 227            | 0.63       |                |            |
| Rice, polished          | 181           | 1.01       |               |            |              |            |                | 0.58       |                |            |
| Wheat flour             | 224           | 1.10       | 102           | 0.50       |              |            |                | 34         |                | 0.17       |
| Wheat kernels           | 1430          | 5.21       | 968           | 3.52       | 38           | 0.14       |                |            |                |            |
| Rye flour               | 666           | 3.98       | 583           | 3.49       | 539          | 3.54       | 244            | 1.46       |                |            |
| Rye flour, whole grain  | 275           | 2.29       |               |            |              |            |                |            |                |            |
| Bread for toasting, white| 236           | 2.56       | 93            | 1.00       | 59           | 0.63       |                |            |                |            |
| Oats                    |               |            |               |            |              |            | 87             | 0.70       |                |            |
| Instant potato flakes   | 263           | 1.26       | 535           | 2.57       | 263          | 1.26       |                |            |                |            |
| Kidney beans            | 555           | 1.73       | 2096          | 6.54       | 1025         | 3.20       | 1390           | 4.34       | 712            | 2.22       |
| Onions                  | 157           | 0.43       |               |            |              |            | 705            | 1.91       |                |            |
| White cabbage           |               |            |               |            |              |            | 548            | 2.74       |                |            |
| Apples                  | 753           | 6.69       |               |            |              |            |                |            |                |            |
| Watermelon              |               |            |               |            |              |            | 347            | 4.16       |                |            |
| Cantaloupes             |               |            |               |            |              |            | 242            | 2.28       |                |            |
| Limes                   |               |            |               |            |              |            | 159            | 5.88       |                |            |
| Olives                  |               |            |               |            |              |            | 5              | 0.12       |                |            |
| Juice, apple            | 230           | 1.52       |               |            |              |            |                |            |                |            |
| Juice, orange           |               |            |               |            |              |            | 230            | 1.68       |                |            |
| Eggs                    | 85            | 2.48       |               |            |              |            | 85             | 2.48       |                |            |
| Medister (sausage)      | 444           | 14.80      |               |            |              |            | 233            | 7.78       |                |            |
| Ham, pork, cured        |               |            |               |            |              |            | 186            | 9.24       |                |            |
| Kidneys, pork           | 873           | 13.71      | 66            | 1.03       | 253          | 3.97       |                |            |                |            |
| Beef, minced, 15%       |               |            |               |            |              |            | 23             | 1.04       |                |            |
| Salami                  |               |            |               |            |              |            | 1              | 0.03       |                |            |
| Chicken, whole          | 85            | 3.30       |               |            |              |            | 53             | 2.06       |                |            |
| Chicken, breast or cut  |               |            |               |            |              |            | 32             | 1.67       |                |            |
| Herring fillets         | 106           | 7.20       | 175           | 11.87      | 112          | 7.62       | 6              | 0.43       |                |            |
| Cod liver, canned       |               |            |               |            |              |            | 16             | 2.20       |                |            |
| Salmon                  |               |            |               |            |              |            | 47             | 3.38       |                |            |
| Sunflower oil           | 151           | 1.69       | 26            | 0.29       | 41           | 0.46       |                |            |                |            |
| Margarine 70% fat       | 5             | 0.05       |               |            |              |            |                |            |                |            |
| Rapeseed oil            | 175           | 2.02       | 91            | 1.06       | 133          | 1.54       |                |            |                |            |
| Mayonnaise              |               |            |               |            |              |            | 11             | 0.23       |                |            |
| Cod liver oil           | 16            | 3.29       | 4             | 0.87       | 8            | 1.58       |                |            |                |            |
| Sugar                   | 142           | 1.41       |               |            |              |            |                | 38         | 0.38           |            |
| Toffee                  |               |            |               |            |              |            | 63             | 6.83       |                |            |
| Sweet drops             |               |            |               |            |              |            | 34             | 2.47       |                |            |
| Chocolate, dark         |               |            |               |            |              |            | 7              | 0.90       |                |            |
| Salt, iodised           | 20            | 0.05       | 2             | 0.01       | 3            | 0.01       |                |            |                |            |
| Sums:                   | 5440          | 56.87      | 6113          | 45.63      | 3735         | 23.98      | 6344           | 52.53      | 5443          | 80.34      |

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availability of a small number of foods. The removal of specific foods that are rich in cost-controlling nutrients such as vitamin D, e.g., cod liver, cod liver oil, and cod roe, more than doubled the cost of FB N (~DKK 41, €5.5). Similarly the removal of iodised salt resulted in an additional cost of DKK 2.7 (€0.4).

An increased number (variety) of foods (Fig 1A) was created by limiting the maximum proportion of each food in all baskets. This resulted in the inclusion of 130 and 135 foods, respectively, in the N and DGN baskets compared with only 70 foods in the CAN. Attempts to increase the number of foods beyond these numbers meant that the applied constraints could no longer be met.

The cost increase was approximately linear (Pearson’s r: 0.936 (CAN) to 0.995 (DG)): it was low for N and CA (DKK 0.34 and 0.35 per additional food item, respectively) and higher for DG, DGN, and CAN (DKK 0.56, 0.59, and 0.63 per food, respectively) (Fig 1B). Out of the basic list of 312 foods, only 23 foods became part of all FBs with extended food variety and 114 were never selected to become part of any FB. Food baskets with an extended food variety contained a large number of foods and could be converted into one-month (30.5 days) baskets for a household (Table 4).

The average relative deviation (ARD) from the usual Danish eating pattern decreased to around two-thirds (60–70%) after 50 foods were added to the basket (Fig 2).

If only cost and cultural acceptability (CA) were considered, the one-day FB was 50–90% deficient in fibre, magnesium, iron, and vitamin C and more than 50% deficient in vitamins A and D (Fig 3A). Similarly, if DG alone was considered, the one-day FB was 50–90% deficient in polyunsaturated and omega-3 FA, vitamins C and E, calcium, iodine, and >50% deficient in vitamins A and D, total lipids, and monounsaturated FA (Fig 3B). The amount of nutrients,
with the exception of vitamin D and monounsaturated FA, in CA and DG increased above 100% of the recommendations after increasing the variety of foods in these FBs (Fig 3).

Although being isocaloric, the diversified N had a considerably lower weight (~4.0 kg) than the other FBs (~5.4–6.3 kg). Implementation of constraints on cultural acceptability (CA) and health promotion (DG) had a stronger influence on the composition of the combined FBs (CAN and DGN) than constraints on nutritional adequacy (N) (Fig 4). Compared to N, CA

table 4. Weight and price of 102 foods in an extensively diversified N food basket (max. share of a single food in each corresponding category: 8%) sufficient to provide 30.5 diversified one-day (= one month) food baskets for a family of four, costing DKK 54 (~€ 7.2) per day.

| Food item | Weight (g) | Cost (DKK) | Food item | Weight (g) | Cost (DKK) | Food item | Weight (g) | Cost (DKK) |
|-----------|------------|------------|-----------|------------|------------|-----------|------------|------------|
| Bread & cereals |          |            | Vegetables |          |            | Milk + milk products |          |            |
| Rice, parboiled | 2123 | 6 | Onions | 1737 | 5 | Milk, skimmed | 3575 | 18 |
| Rice, polished | 2123 | 7 | Kidney beans | 1737 | 5 | Milk, 0.5% | 3575 | 18 |
| Pasta | 2123 | 7 | Carrots | 1737 | 8 | Milk, 1.5% | 3575 | 20 |
| Wheat kernels | 2123 | 8 | White cabbage | 1737 | 9 | Milk, 3.5% | 3575 | 21 |
| Wheat flour | 2123 | 10 | Green lentils | 1737 | 12 | Yogurt 1.5% | 2888 | 29 |
| Rye flour | 2123 | 13 | Soy beans, peeled | 1737 | 13 | Crème fraîche 38% | 2825 | 56 |
| Rice, whole grain | 2123 | 13 | Red cabbage | 1737 | 15 | Buttermilk, 0.5% | 1637 | 11 |
| Noodles (pasta with egg) | 2123 | 15 | White beans, small | 1737 | 17 | Yogurt 3.5% | 666 | 8 |
| Barley flour | 2123 | 15 | Chickpeas | 1737 | 18 | Soured milk 3.5% | 666 | 9 |
| Oats | 2123 | 17 | Tomato Ketchup | 1737 | 18 | Greek yogurt 10% | 232 | 4 |
| Rye flour, whole grain | 2123 | 18 | Spinach | 1737 | 19 | Meat | Kids, pork | 1083 | 17 |
| Wheat flour, whole grain | 2123 | 21 | Cauliflower | 1354 | 10 | Kidneys, veal | 200 | 6 |
| Whole grain rye bread | 2123 | 22 | Avocado | 1354 | 23 | Salami | 200 | 7 |
| Toast, whole grain | 2123 | 23 | Celeriac | 1227 | 11 | Heart, pork | 200 | 10 |
| Baguette | 2123 | 23 | Kidney beans, canned | 969 | 12 |                     |          |            |
| Bread for toasting, white | 2123 | 23 | Black beans, turtle | 969 | 19 | Fish | Cod liver, canned | 259 | 37 |
| Pita bread | 2123 | 32 | Tomatoes, dried | 969 | 51 | Mackerel, filet | 118 | 12 |
| Corn starch | 1967 | 33 | Red lentils | 581 | 10 | Salmon | 78 | 6 |
| Couscous | 1625 | 11 | Soy beans, in husk | 111 | 5 | Trout, whole | 78 | 10 |
| Pasta, whole grain | 1625 | 17 | Parsley | 43 | 1 | Cod roe | 78 | 8 |
| Ciabatta | 1594 | 32 | Oranges | 1837 | 18 |                     |          |            |
| Bulgur | 1069 | 8 | Cantaloupes | 1144 | 11 | Sardines in vegetable oil | 37 | 5 |
| Spelt flour, whole grain | 1069 | 12 | Raisins | 1080 | 34 | Tuna, fresh | 37 | 5 |
| Pearl barley | 1069 | 15 | Fruit jam | 1019 | 17 |                     |          |            |
| Tortillas | 1069 | 24 | Dates, dried | 405 | 15 | Sardines | 37 | 5 |
| Bread, wholemeal | 1069 | 27 | Kiwis | 327 | 6 | Place | 37 | 5 |
| Cornmeal | 1069 | 35 | Prunes | 47 | 2 | Trout filet, smoked | 37 | 7 |
| Muesli (Fruit and Nuts) | 1069 | 43 | Marmalade | 12 | 0.3 |                     |          |            |
| Potatoes & potato products |          |            | Fats & oils |          |            | Margarine 70% fat | 381 | 4 |
| Instant potato flakes | 642 | 3 | Orange juice | 561 | 4 | Sunflower oil | 381 | 4 |
| Potatoes | 642 | 4 | Nuts & seeds |          |            | Rapeseed oil | 381 | 4 |
| Potato flour | 642 | 6 | Sunflower kernels | 1837 | 41 | Mayonnaise | 381 | 8 |
| Frozen chips | 642 | 8 | Coconuts | 1391 | 19 | Cod liver oil | 381 | 79 |
| Frozen roast potatoes | 642 | 12 | Sesame seeds | 976 | 51 | Corn oil | 362 | 8 |
| Potato crisps | 642 | 17 | Peanuts, oil-roasted | 922 | 44 | Butter, with salt | 351 | 13 |
| Frozen potato wedges | 195 | 3 | Coconut meat, dried | 222 | 7 | Olive oil | 295 | 11 |
| Sugar | 346 | 3 | Walnuts, w/ shell | 75 | 9 |                     |          |            |
| Salt, iodised | 221 | 1 | Eggs | 88 | 3 | Grapeseed oil | 61 | 2 |
| Salt | 221 | 1 | Cheese | 200 | 7 | Duck fat | 3 | 0.5 |

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and CAN contained more milk(products), fruits, and meat and DG and DGN contained more cereals, vegetable, fruits and offal (Fig 4).

Already a moderate release of the cultural acceptability constraint MRD (10% deviation from the averagely consumed weight of each food category allowed) resulted in a significant drop in the minimal cost and increased food variety of CAN (Fig 5). After increasing the MRD to 20%, food variety did not increase further and additional increase of MRD resulted in reduced cost only. Allowing a 40% MRD resulted in a food variety that was comparable to that of N and cost only ~DKK 1 (€ 0.13) more than N.

**Discussion**

The present study shows that a systematically structured approach using LP to increase the variety of foods illustrates how culturally acceptable FBs can be constructed for the lowest possible cost.

Similar to earlier investigations it was found that very few foods are needed to meet both nutrient and dietary recommendations for the lowest cost [19]. The Danish FBDGs, when applied as constraints during the construction of FBs with increased food variety, appear to result in coverage of all recommended intakes [6] except vitamin D and monounsaturated FA (Fig 3). One of the advantages of using a methodology such as LP is that it provides a systematic approach to confirm e.g. in dietary guidelines whether or not nutritionally adequacy is assured in different contexts for different populations.
This study illustrates how a low cost diet can be designed to be both nutritionally adequate and to prevent NCDs in the Danish population. The cost was primarily determined by key micronutrients: vitamins D, C, B2 and iodine, potassium, and calcium. When these key nutrients were incorporated at the recommended levels all other macro- and micro-nutrients were automatically present in sufficient amounts. The lowest cost was best achieved by including the foods that contain high levels of these key nutrients: whole-grain products, root vegetables, fatty fish and milk. The important role of foods rich in vitamin D was also recognised by Swedish [30] and Slovenian investigators (Gregoric et al., unpublished report for the Ministry of Labour, Family and Social Affairs of Slovenia, 2009). It may be difficult to cover vitamin D recommendations from foods alone [38] and exposure to sunlight (UV-B) is also recommended [39]. Alternatively, vitamin D supplements or vitamin D fortification [40] may be recommended especially during the winter and early spring in the Northern hemisphere [41].

One of the strengths of the LP-model is that it can facilitate the generation of a household food basket for the period of one month, or longer or shorter, at the lowest possible cost and enables recipe development for complete meals (Table 4). The minimum cost of the one-month household FB of type N for a Danish family of four was ~DKK 54 (~€ 7.2) per day. This cost is similar to that found by French investigators (~€ 3.20 and ~€ 3.40 per day for a woman and man, respectively) [42] but less than half that found in the United States (~$ 18.60, ~€ 17, for a family of four) [43]. In 2007, Danish investigators estimated that a Danish family, following the official Danish FBDGs, would have to spend on average DKK 171 (~€ 23) per day [44], corresponding to between 3-fold the cost of N and about 40% more than the cost of CAN, based on average Danish food prices. In 2010, Danish statisticians reported that the average Danish household (2 adults and 1.8 children) actually spent DKK 140 (~€ 19) on their

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**Fig 3. Effects of diversification through lowering the maximum allowed relative share of a single food within each food category on the contents of nutrients that were below 95% of the RI in the non-diversified form (Table 3) A) Food basket CA B) Food basket DG. Abbreviations: Vit: vitamin; RAE: retinol equivalent units; n-3 FA: omega-3 fatty acids; FA mono: monounsaturated fatty acids; FA poly: polyunsaturated fatty acids.**

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household food budget, excluding foods bought outside the home [45]. Lower socioeconomic households spend around 20–25% less than the higher socioeconomic households (standardized for household size and composition). However, based on the average disposable income for two Danish adults on average salaries and using the DGN model, between 6% and 11% of their household income is needed to cover its cost. In contrast, families suffering from unemployment or dependent on benefits would have to spend between 10% and 18% of their income [46]. The percentage of disposable income needed in Ireland to cover the cost of a healthy diet was estimated to be up to 69% of income [47], between 30% and 48% in Australia [48,49] and 30% in Canada [50]. In addition to the differences in national food prices, this wide range in % income probably arises from the different methods available to calculate the cost of a healthy diet. One advantage of the LP method is that so-called “unhealthy” foods (i.e. those with unfavourable nutrient profiles) can be combined with “healthy” foods to design an overall healthy diet [51].
Most consumers are unlikely to adopt food basket recommendations unless they consider these practical, feasible, culturally acceptable, familiar and sufficiently varied in number [42]. Consumers in France eat on average around 50 different foods per week [52] compared with the household food basket for a month in this study, which contains twice that number (Table 4). Eating patterns are notoriously difficult to change. There are many barriers e.g. cost, taste, habit and others to changing to a healthy diet [53] especially in low socioeconomic groups. For example in Denmark, consumers prefer meat, meat products, eggs, sweets, sugar-sweetened soft drinks, and alcoholic drinks [26]. However when these foods were selected by the linear programming method, e.g. because of their cultural acceptability only, the overall cost increased and it was not possible to meet the nutrient and dietary recommendations. Indeed the gap between a culturally acceptable diet and the Nordic nutrition recommendations
is wide. Almost no meat, juice, and sweets and considerably less milk products were in the LP designed food baskets of types DG and DGN. In contrast, they contained more than twice as much cereals and vegetables and more liver compared with the CA. The required change seems quite dramatic and so households have to be quite determined and resourceful to incorporate these newly designed FBs into their daily routine and to compile this big change in food variety into new recipes and meals that their families will eat. Cultural acceptability, however, can only be achieved at the expense of cost (Fig 5) and in some cases inability to meet nutrient recommendations.

The cost data presented here are based on the purchase price alone. However foods once purchased have to be converted into appetising meals and so additional resources are needed for: transport; equipment; storage, preparation and cooking facilities; utensils to serve meals; energy for hot water, food storage and preparation (refrigerating, freezing, cooking); time to prepare meals (and assuming person preparing food might otherwise be earning) [54,55]; drinks, spices, and unavoidable food waste. Food prices vary due to different national retail policies, marketing practices, fixed retail packaging sizes, seasonal local availability and price fluctuations, and volatility on the global market [56]. There are also hidden costs related to how households can plan and cook new recipes and prepare meals. Similarly, households’ nutritional needs vary depending on its number of inhabitants, their age and level of physical activity and whether or not they suffer from overweight. Therefore food baskets must be calculated at a national or sub-national level to consider the local context and costs. Indeed a reliable, sufficiently detailed, international database on food prices [57] would facilitate the possibility of authorities being able to design relevant food baskets and dietary guidelines using the LP methodology.

**Conclusion**

Nutritional adequacy, health-promoting, NCD-preventing properties, and cultural acceptability are all constraints that need to be addressed and LP is a method that can help solve this complex task. When designing low cost national food baskets their feasibility and implementation has to be investigated via intervention studies. Feasible food baskets, which are readily accepted by low socioeconomic groups, could serve as the basis for national food based dietary guidelines that can help reduce diet-related health inequalities. National and international authorities could, by using linear programming methods, design dietary guidelines that are more cost-effective in preventing micronutrient deficiencies and diet-related NCDs.

**Supporting Information**

**S1 Table. Food Prices in the Larger Copenhagen Area.** The file provides the food category, the name of the food item, and the corresponding average, maximum, and minimum price. (CSV)

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References
1. Robertson A, Lobstein T, Knai C. Obesity and socio-economic groups in Europe: Evidence review and implications for action. Contract report SANCO/2005/C4-NUTRITION-03, 2007 [cited 2015 Oct 3]. Available from: http://ec.europa.eu/health/ph_determinants/life_style/nutrition/documents/ev20081028_rep_en.pdf.
2. Miller R, Spiro A, Stanner S. Micronutrient status and intake in the UK–where might we be in 10 years time? Nutr Bull. 2016; 41:14–41. doi: 10.1111/nbu.12187
3. Brough L, Rees GA, Crawford MA, Morton RH, Dorman EK. Effect of multiple-micronutrient supplementation on maternal nutrient status, infant birth weight and gestational age at birth in a low-income, multi-ethnic population. Br J Nutr. 2010; 104:437–45. doi: 10.1017/S0007114510000747 PMID: 20412605
4. Eden AN. Iron deficiency and impaired cognition in toddlers: an underestimated and undertreated problem. Paediatr Drugs. 2005; 7:347–52. doi: 10.2165/00148581-200507060-00003 PMID: 16356022
5. Swinburn BA, Caterson I, Seidell JC, James WP. Diet, nutrition and the prevention of excess weight gain and obesity. Public Health Nutr. 2004 Feb; 7(1A):123–46. doi: 10.1079/phin2003585 PMID: 14972057
6. Nordic Council of Ministers. Nordic Nutrition Recommendations 2012. Integrating nutrition and physical activity. 5th edition, 2014. Narayana Press, Odder, Denmark. [cited 2015 Nov 12]. Available from: http://norden.diva-portal.org/smash/record.jsf?pid=diva2%3A704251&dswid=-372.
7. Jones NR, Conklin AI, Suhrcke M, Monsivais P. The growing price gap between more and less healthy foods: analysis of a novel longitudinal UK dataset. PLoS One. 2014 Oct 8; 9(10):e109343. doi: 10.1371/journal.pone.0109343 eCollection 2014 PMID: 25296332
8. Darmon N, Ferguson EL, Briend A. A cost constraint alone has adverse effects on food selection and nutrient density: an analysis of human diets by linear programming. J Nutr. 2002; 132:3764–71. PMID: 12468621
9. Troesch B, Biesalski HK, Bos R, Buskens E, Calder PC, Saris WHet al. Increased Intake of Foods with High Nutrient Density Can Help to Break the Intergenerational Cycle of Malnutrition and Obesity. Nutrients. 2015; 7:6016–37. doi: 10.3390/nu7075266 PMID: 26197337
10. Toft U, Vinding AL, Larsen FB, Hvidberg MF, Robinson KM, Glümer C. The development in body mass index, overweight and obesity in three regions in Denmark. Eur J Public Health. 2015; 25:273–8. doi: 10.1093/eurpub/cku175 PMID: 25414483
11. World Health Organization. Obesity and overweight. Fact sheet N°311, updated January 2015. 2015. [cited 2016 Apr 28]. Available from: http://www.who.int/mediacentre/factsheets/fs311/en/.
12. Webber L, Divajeva D, Marsh T, McPherson K, Brown M, Galea G, et al. The future burden of obesity-related diseases in the 53 WHO European-Region countries and the impact of effective interventions: a modelling study. BMJ Open. 2014 Jul 25; 4(7):e004787. doi: 10.1136/bmjopen-2014-004787 PMID: 25063459
13. Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H et al. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet 2012; 380:2224–60. doi: 10.1016/S0140-6736(12)61766-8 PMID: 23245609

14. World Health Organization. Vienna Declaration on Nutrition and Noncommunicable Diseases in the Context of Health 2020. 2013 [cited 2015 June 16]. Available from: http://www.euro.who.int/__data/assets/pdf_file/0009/193878/Vienna-Declaration.pdf

15. Aggarwal A, Monsivais P, Cook AJ, Drewnowski A. Does diet cost mediate the relation between socioeconomic position and diet quality? Eur J Clin Nutr. 2011; 65:1059–66. doi: 10.1038/ejcn.2011.72 PMID: 21559042

16. Di Cesare M, Khang YH, Asaria P, Blakely T, Cowan MJ, Farzadfar F, et al. Inequalities in non-communicable diseases and effective responses. Lancet. 2013; 381:585–97. doi: 10.1016/S0140-6736(12)61851-0 PMID: 23410608

17. Magnusson M, Sørensen TI, Olafsdottir S, Lehtinen-Jacks S, Holmen TL, Heitmann BL et al. Social inequalities in obesity persist in the Nordic region despite its relative affluence and equity. Curr Obes Rep. 2014; 3:1–15. doi: 10.1007/s13679-013-0087-2 PMID: 24533235

18. Knudsen VK, Fagt S, Trolle E, Mattheissien J, Groth MV, Biltoft-Jensen A et al. Evaluation of intake in Danish adults by means of an index based on food-based dietary guidelines. Food Nutr Res. 2012; 56. doi: 10.3402/fnr.v56i17129 Epub 2012 Apr 20. PMID: 22529769

19. Smith VE. Linear programming models for the determination of palatable human diets. J Farm Econ 1959; 41:272–83. doi: 10.2307/1235154

20. Darmon N, Ferguson E, Briënd A. Linear and nonlinear programming to optimize the nutrient density of a population’s diet: an example based on diets of preschool children in rural Malawi. Am J Clin Nutr. 2002; 75:245–53. PMID: 11815314

21. Parlesak A, Geelhoed D, Robertson A. Toward the prevention of childhood undernutrition: diet diversity strategies using locally produced food can overcome gaps in nutrient supply. Food Nutr Bull. 2014; 35:191–9. doi: 10.1177/014082651403500205 PMID: 25076766

22. Ferguson EL, Darmon N, Briënd A, Premachandra IM. Food-based dietary guidelines can be developed and tested using linear programming analysis. J Nutr. 2004; 134:951–7. PMID: 15051853

23. Ontario Ministry of Health Promotion. Nutritious Food Basket Guidance Document, February 2010. [cited 2015 Aug 30]. Available from: http://www.health.gov.on.ca/enGLISH/providers/program/pubhealth/oph_standards/ophs/guidance.html.

24. Williams P. Monitoring the affordability of healthy eating: a case study of 10 years of the Illawarra Healthy Food Basket. Nutrients. 2010; 2:1132–40. doi: 10.3390/nu211132 PMID: 22254001

25. Carlson A, Lino M, Juan WY, Hanson K, Basiotis PP. Thrifty Food Plan 2006 (CNPP-19). US Department of Agriculture, Center for Nutrition Policy and Promotion; 2007 [cited 2016 April 4]. Available from: http://www.cnpp.usda.gov/sites/default/files/usda_food_plans_cost_of_food/TFP2006Report.pdf.

26. Pedersen AN, Christensen T, Matthiessen J, Kidegaard Knudsen V, Rosenlund-Sørensen M, Biltoft-Jensen A, et al. Danskerne kostvaner 2011–2013 –Hovedresultater. DTU Fødevareinstituttet, Afdeling for Ernærning, 2014. [cited 2015 Sep 8]. Available from: http://www.food.dtu.dk/~media/Institutter/ Foedevareinstituttet/Publikationer/Pub-2015/Rapport%20%20Danskerne%20%20Kostvaner%20%202011-2013.ashx?la=da.

27. Ministry of Food, Agriculture and Fisheries of Denmark. De officielle kostråd. 2014 [cited 2015 Oct 15]. Available from: http://altomkost.dk/raad-og-anbefalinger/de-officielle-kostraad/.

28. Hatloy A, Torheim LE, Oshaug A. Food variety—a good indicator of nutritional adequacy of the diet? A case study from an urban area in Mali, West Africa. Eur J Clin Nutr. 1998; 52:891–8. PMID: 9881884

29. Bernstein MA, Tucker KL, Ryan ND, O’Neill EF, Clements KM, Nelson ME, et al. Higher dietary variety is associated with better nutritional status in frail elderly people. J Am Dietetic Assoc. 2002; 102:1096–104. doi: 10.1016/s0002-8223(02)90246-4 PMID: 12171454

30. Håkansson A. Has it become increasingly expensive to follow a nutritious diet? Insights from a new price index for nutritious diets in Sweden 1980–2012. Food Nutr Res. 2015; 59:26932. doi: 10.3402/fnr.v59.26932 PMID: 25862145

31. Saxholt E, Christensen AT, Møller A, Hartkopp HB, Hess Ygil K, Hels OH. Danish Food Composition Database, revision 7. Department of Nutrition, National Food Institute, Technical University of Denmark. 2008. Available from: http://www.foodcomp.dk/.

32. United States Department of Agriculture, 2014. The USDA National Nutrient Database for Standard Reference SR28. [Online] [cited 2015 November 17]. Available from: http://ndb.nal.usda.gov/.
33. Prüß U, Hüther L, Hohgardt K. Mittlere Gewichte einzelner Obst- und Gemüseerzeugnisse (Mean Single Unit Weights of Fruit and Vegetables). Bundesamt für Verbraucherschutz und Lebensmittelsicherheit. 2004. [cited 2015 November 28]. Available from: http://www.bvl.bund.de/SharedDocs/Downloads/04_Pflanzenschutzmittel/rueckst_gew_obst_gem%C3%BCde_pdf.pdf?__blob=publicationFile.

34. Dantzig GB. Maximization of a linear function of variables subject to linear inequality. 1947. Published in Koopmans T.C. (ed.): Activity analysis of production and allocation. 1951. Wiley & Chapman-Hall, New York-London; pp. 339–47

35. Mason AJ. “OpenSolver—An open source add-in to solve linear and integer programmes in Excel”, Operations Research Proceedings 2011. eds.

36. Denmarks Statistik [Internet]. Statistikbanken. FAM44N: Familier 1. januar efter kommune, familietype, familiestørrelse og antal børn. 2015a [cited 2015 June 8]. Available from: http://www.statistikbanken.dk/statbank5a/default.asp?w=1680.

37. Nocedal J, Wright SJ. Numerical Optimization (2nd ed.). Berlin, New York: Springer-Verlag. 2006. pp 304–54.

38. Holick MF. Vitamin D deficiency. N Engl J Med. 2007; 357:266–81.

39. Landin-Wilhelmsen K, Wilhelmsen L, Wilske J, Lappas G, Rosén T, Lindstedt G, et al. Sunlight increases serum 25(OH) vitamin D concentration whereas 1,25(OH)2D3 is unaffected. Results from a general population study in Göteborg, Sweden (The WHO MONICA Project). Eur J Clin Nutr. 1995; 49:400–7. PMID: 7656883

40. Lamberg-Allardt C, Brustad M, Meyer HE, Steinrimsdottir L. Vitamin D—a systematic literature review for the 5th edition of the Nordic Nutrition Recommendations. Food Nutr Res. 2013; 57. doi: 10.3402 fnr.v57i0.22671 eCollection 2013

41. Virtanen JK, Nurm I, Voutilainen S, Mursu J, Tuomainen TP. Association of serum 25-hydroxyvitamin D with the risk of death in a general older population in Finland. Eur J Nutr. 2011; 50:305–12. doi: 10.1007/s00394-010-0138-3 PMID: 20976461

42. Maillot M, Darmon N, Drewnowski A. Are the lowest-cost healthful food plans culturally and socially acceptable? Public Health Nutr. 2010; 13:1178–85. doi: 10.1017/S136890009993028 PMID: 20105388

43. Center for Nutrition Policy and Promotion, United States Department of Agriculture. USDA Food Plans: Cost of Food report for March 2015; 2015 [cited 2015 May 10] Available from: http://www.cnpp.usda.gov/sites/default/files/CostofFoodMar2015.pdf.

44. Gille MB, Bittoff-Jensen A, Silkeborg Brolev K, Bechmann Christensen M, Deijgaard Jensen J, Kraup Rask I, et al. Undersøgelse af merudgifter til diabeteskost 2007–2008. 2008 [cited 2015 Sep 25]. Available from: http://www.diabetes.dk/media/47709/Rapport_kostundersoegelsen.pdf.

45. Denmarks Statistik [Internet]. Statistikbanken. FU51: Husstandenes årlige forbrug efter forbrugsart, husstandsgrupper og prisenhed. 2015b. [cited 2015 June 8]. Available from: http://www.statistikbanken.dk/statbank5a/default.asp?w=1680.

46. Denmarks Statistik [Internet]. Statistikbanken. LONS20: Earnings by occupation, sector, salary, salary earners, components and sex. 2015c. [cited 2015 June 9]. Available from: http://www.statbank.dk/KUBESK4.

47. Friel S, Walsh O, McCarthy D. The irony of a rich country: issues of financial access to and availability of healthy food in the Republic of Ireland. J Epidemiol Community Health. 2006; 60:1013–9. doi: 10.1136/jech.2005.041335 PMID: 17108295

48. Barosh L, Friel S, Engelhardt K, Chan L. The cost of a healthy and sustainable diet—who can afford it? Aust NZ J Public Health. 2014; 38:7–12. doi: 10.1111/1753-6405.12158 PMID: 24494938

49. Ward PR, Verity F, Carter P, Tsourtos G, Coveney J, Wong KC. Food stress in Adelaide: the relationship between low income and the affordability of healthy food. J Environ Public Health. 2013; 2013:968078. doi: 10.1155/2013/968078 PMID: 23431321

50. Newell FD, Williams PL, Watt CG. Is the minimum enough? Affordability of a nutritious diet for minimum wage earners in Nova Scotia (2002–2012). Can J Public Health. 2014 May 9; 105(3):e158–65. PMID: 25165833

51. Maillot M, Drewnowski A, Vieux F, Darmon N. Quantifying the contribution of foods with unfavourable nutrient profiles to nutritionally adequate diets. Br J Nutr. 2011; 105:1133–7. doi: 10.1017/ S0007114510004800 PMID: 21140095

52. Dubuisson C, Liotet S, Touvier M, Dufour A, Calamassi-Tran G, Volatier JL, et al. Trends in food and nutritional intakes of French adults from 1999 to 2007: results from the INCA surveys. Br J Nutr. 2010; 103:1035–48. doi: 10.1017/S0007114509992625 PMID: 20028601
53. Beck TK, Jensen S, Simmelsgaard SH, Kjeldsen C, Kidmose U. Consumer clusters in Denmark based on coarse vegetable intake frequency, explained by hedonics, socio-demographic, health and food lifestyle factors. A cross-sectional national survey. Appetite. 2015; 91:366–74. doi: 10.1016/j.appet.2015.04.060 PMID: 25916624

54. Davis G, You W. Not enough money or not enough time to satisfy the Thrifty Food Plan? A cost difference approach for estimating a money-time threshold. Food Policy. 2011; 36:101–7. doi: 10.1016/j.foodpol.2010.09.001

55. Monsivais P, Aggarwal A, Drewnowski A. Time spent on home food preparation and indicators of healthy eating. Am J Prev Med. 2014; 47:796–802. doi: 10.1016/j.amepre.2014.07.033 PMID: 25245799

56. Leather S. Less money, less choice: poverty and diet in the UK. In Your food: whose choice? National Consumer Council (eds.), Your food, whose choice? HMSO, London 1992. pp. 72–94.

57. Lee A, Mhurchu CN, Sacks G, Swinburn B, Snowdon W, Vandevijvere S, et al. Monitoring the price and affordability of foods and diets globally. Obes Rev. 2013; 14 Suppl 1:82–95. doi: 10.1111/obr.12078 PMID: 24074213