Journal of Cleaner Production 236 (2019) 117645

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Concurrent economic and environmental impacts of food consumption: are low emissions diets affordable?

Luca Benvenuti [a,*], Alberto De Santis [a], Andrea Di Sero [a], Nicola Franco [b]

[a] Department of Computer, Control, and Management Engineering, Sapienza University of Rome, Via Ariosto 25, 00185, Roma, Italy
[b] Italian Association for Dietetics and Clinical Nutrition, Italy

A R T I C L E I N F O

Article history:
Received 22 January 2019
Received in revised form
9 July 2019
Accepted 13 July 2019
Available online 17 July 2019

Handling editor: Dr. Govindan Kannan

Keywords:
Food consumption pattern
Environmental sustainability
Economic sustainability

A B S T R A C T

Sustainability of food consumption concerns both environmental and economic issues. In fact, the United Nations Food and Agricultural Organization defines as sustainable diets those that are protective and respectful of ecosystems, culturally acceptable, economically affordable, besides ensuring an adequate and healthy nutrition.

In this paper, a systematic methodology to plan menus complying with nutritional and health issues, close to current eating habits, affordable and with low greenhouse gas emissions is presented. The methodology relies on a multi−objective optimization model with binary variables. The objectives, that is the greenhouse gas emissions needed to serve the menu and its price, are conflicting and therefore a trade−off has to be established by means of the set of Pareto solutions. Any such a solution delivers a menu in term of the recipes composing each daily meal. The application of the presented methodology to the case of cycle menus for nursing homes is investigated. The case study shows that the menu's environmental impact is generally in inverse proportion to its price. Nevertheless, it is possible to obtain a menu with a significantly reduced environmental impact at an affordable extra cost.

1. Introduction

This study addresses the design of sustainable menus served in facilities with service canteens, such as schools, hospices, hospitals, companies, chain restaurants or other individual establishments. According to the UN Food and Agricultural Organization (FAO, 2010), sustainable diets are those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy. As a matter of fact, food production and consumption heavily impact on the environment through, for example, greenhouse gas emissions (GHGE), the use of land and water resources, pollution, depletion of phosphorus, and the impact of chemical products such as herbicides and pesticides. For example, food systems[1] release into the atmosphere up to 17,000 megatonnes of GHGE and agricultural production contributes 80% to these emissions (Vermeulen et al., 2012). On the other hand, the livestock sector alone contributes an estimated 7,100 megatonnes of GHGE per year (Gerber et al., 2013). Consumption patterns are then of great concern since they dictate the shape of the global food production system. For instance, consistent evidence indicates that a dietary pattern higher in plant-based foods (e.g., vegetables, fruits, legumes, seeds, nuts, whole grains) and lower in animal-based foods (especially red meat), as well as lower in total energy, is both healthier and associated with a lesser impact on the environment (Nelson et al., 2016; DGAC SR, 2015).

These considerations call for the definition of consumption patterns with reduced environmental impact (UNEP, 2012). Indeed, one goal in the 2030 Agenda for Sustainable Development (UN, 2015), adopted by all United Nations Member States in 2015, is that of ensuring sustainable consumption and production patterns. As pointed out in this agenda, while substantial environmental impacts from food occur in the production phase (agriculture, food processing), households influence these impacts through their dietary choices and habits. As a matter of fact, quoting (Mertens et al.,

* Corresponding author.
E-mail address: luca.benvenuti@uniroma1.it (L. Benvenuti).

[1] The food system is the collection of all those activities involving the production, processing, transport and consumption of food. It includes growing, harvesting, processing, packaging, transporting, marketing, consumption, and disposal of food and food-related items.

https://doi.org/10.1016/j.jclepro.2019.117645
0959-6526/

2017), “shifting towards a more sustainable food consumption pattern is an important strategy to mitigate climate change. In the past decade, various studies have optimized environmentally sustainable diets using different methodological approaches. In the context of operationalizing the health aspects, diet modelling might be considered the preferred approach since it captures the complexity of the diet as a whole”.

In this context, the aim of this study is to define a systematic methodology to plan menus complying with nutritional and health issues, close to current eating habits, with low GHGE[2] and affordable. To this end, a multi−objective optimization model is developed that allows to define a cycle menu by allocating recipes, from a given set, in the meals of each day while making a trade−off between GHGE and price. The model takes into account factors of different nature such as the content of energy and several nutrients (carbohydrates, proteins, fats, vitamins, minerals, …), the level of consumption of some selected food groups and the structure of the meals according to people food habits. The methodology delivers a menu in terms of the recipes composing each daily meal.

Indeed, linear programming techniques have been applied to a variety of diet problems, from food aid, national food programmes, and dietary guidelines to individual issues. A systematic literature review of the application of linear programming to optimize diets with nutritional, economic, and environmental constraints is proposed in (van Dooren, 2018). The interested reader may refer to the papers therein cited and in particular to (Donati et al., 2016; Macdiarmid et al., 2012; Masset et al., 2009; van Dooren et al., 2015; Wilson et al., 2013) for further information and to gain more insight into the general problem. Basically, these works provide food plans that best resemble current eating habits while meeting nutritional, environmental and cost constraints. The proposed food plans prescribe the level of consumption of selected food groups (such as fruit and vegetables, dairy, meat, fish, …) or food items (potatoes, carrots, beans, eggs, …) for person a day or a week. The plans are obtained by a constrained linear optimization problem where the variables are continuous and consist of the consumption levels of the selected food items, the objective function to be minimized is either the total cost or the GHGE of weekly food consumption (or a linear combination of them), and the constraints depend on nutritional and health issues. No practical menus are provided in these works and only in (Macdiarmid et al., 2012) a sample weekly menu is proposed in order to test whether the food items and the corresponding consumption levels in the optimal food plan can be heuristically combined into a realistic menu. Moreover, quoting (van Dooren, 2018), “most studies use nutritional constraints and cost constraints in the analysis of dietary problems and solutions, but such research begin showing weaknesses under situations featuring a small number of food items and/or nutritional constraints. Introducing acceptability constraints is recommended, but no study provides the ultimate solution to calculating acceptability”.

The methodology proposed in this paper directly provides realistic menus taking into account accepatbility issues. To do this, a large set of recipes with fixed serving size is considered and the menu is the composition and the sequence of daily meals using these recipes. Hence, the variables are binary and describe the presence or absence of each recipe in each meal. Therefore, a more complex optimization problem is obtained, that is a 0−1 integer linear programming problem. Moreover, in the present work, two conflicting priorities are considered, that is the GHGE and the price of the menu so that a multi-objective optimization problem has to be solved considering the trade-off between these conflicting objectives. A similar approach, that is 0−1 integer linear programming problem, is proposed in (Ribal et al., 2016) but a single meal per day and a very small number of recipes are considered, so that acceptability constraints result to be very basic. Moreover, nutritional constraints are considered only over the entire menu thus resulting unrealistic from nutritionists' point of view. Finally, a single-objective optimization problem is considered taking as objective function a linear combination of the positive deviations of GHGE and cost from a given goal, and the daily positive and negative deviations of caloric content from given upper and lower bounds.

The methodology proposed in this paper can be directly applied to define menus for establishments with canteens and the case study of a nursing home food service is presented. A two weeks cycle menu that guarantees nutrients to be in prescribed reference ranges, recommended levels of consumption of some selected food groups and meals structured according to people eating habits, is designed. As a result, the case study shows that the environmental impact of a menu is generally in inverse proportion to its price. Hence, environmental friendly menus are more expensive. Nevertheless, it is possible to tradeoff the menu environmental impact with its economic one, decreasing significantly the level of GHGE with a very low increment of price.

The paper is organized as follows: in Section 2, methods and materials are presented. In more detail, in Section 2.1 the optimization model is illustrated by defining the objective function and the problem constraints. The case study is illustrated in Section 2.2. Results are presented and discussed in Section 3 and conclusions given in Section 4.

2. Methods and materials

The main goal of this study is to define a systematic methodology to design menus taking into account their environmental and economic impacts. To this end a model to describe the scheduling of some recipes in a menu is defined. This model can handle a full-board menu and is an extension of that presented in (Benvenuti et al., 2016) where a single−lunch menu was considered.

2.1. The optimization model

The model describes the scheduling of recipes to be served in a cycle menu taking into account its economic and environmental impacts, the nutritional and health characteristics as well as acceptability of the menu itself. The model allows to choose the composition and the sequence of daily meals using items within a given set composed of N different recipes with fixed serving size. The data needed to construct the model are the nutritional values of each recipe, its price and the quantity of greenhouse gases emitted in the atmosphere to produce its ingredients. Therefore, a set F of features such as *price*, *GHGE* and several nutrients (carbohydrates, proteins, fats, vitamins, minerals, …) is associated to each recipe and the corresponding quantities are computed from available databases. Nutritional recommendations are mainly defined by suitable reference ranges on daily nutrient intakes, while health recommendations regard reference levels of consumption for some food groups. On the other hand, acceptability concerns meals structure and recipe repetitions in the menu. The menu is designed using the proposed model by optimizing the economic impact and the environmental one and it is guaranteed to satisfy nutritional, health and acceptability constraints. The model can handle half board menus, full board menus or, in general, menus with a number of N_M meals per day. Moreover, the service can be full week, as for example in hospitals, or workweek, as for company canteens. In

[2] GHGE here considered consists of that resulting from the life cycle assessment at farm gate calculated as carbon dioxide equivalent (CO_{2eq}).

general, the model may consider services over a number N_D of days in a week. Let us associate to each recipe a binary variable $x^i_{m,d,w}$ that assumes value 1 if the recipe $i \in I = \{1, \ldots, N\}$ is part of the meal m of the day d in the week w, and 0 otherwise. The index m takes values in a subset $M \subseteq \{breakfast, mid-morning\ snack, lunch, mid-afternoon\ snack, dinner\}$ while the index d takes values in a subset $D \subseteq \{Mon, Tue, Wed, Thu, Fri, Sat, Sun\}$. Finally, the index w takes values in a set $W = \{1, \ldots, N_W\}$ for a menu of $N_W \geq 1$ weeks. Therefore, the model produces a cycle menu represented as a tuple $x = \{x^i_{m,d,w}\}$ which takes value in

$$X = \{0, 1\}^{N \times N_M \times N_D \times N_W}$$

2.1.1. Objective function

Let Q^f_i be the quantity of the feature $f \in F$ of the recipe i. Then, the feature quantity $Q^f_{m,d,w}(x)$ of the meal m in the day d of the week w is

$$Q^f_{m,d,w}(x) = \sum_{i \in I} x^i_{m,d,w} \cdot Q^f_i \tag{1}$$

As a consequence, the feature quantity $Q^f_{d,w}(x)$ of all the meals of the day d in the week w is

$$Q^f_{d,w}(x) = \sum_{m \in M} Q^f_{m,d,w}(x) = \sum_{m \in M} \sum_{i \in I} x^i_{m,d,w} \cdot Q^f_i \tag{2}$$

Finally, the features quantities $Q^f_w(x)$ and $Q^f(x)$ of all the meals in the week w and of the entire menu, respectively, are

$$Q^f_w(x) = \sum_{d \in D} Q^f_{d,w}(x) = \sum_{d \in D} \sum_{m \in M} \sum_{i \in I} x^i_{m,d,w} \cdot Q^f_i \tag{3}$$

and

$$Q^f(x) = \sum_{w \in W} Q^f_w(x) = \sum_{w \in W} \sum_{d \in D} \sum_{m \in M} \sum_{i \in I} x^i_{m,d,w} \cdot Q^f_i \tag{4}$$

The optimal menu is supposed to minimize price and GHGE, therefore the following multi−objective optimization problem has to be solved:

$$\min_{x \in \mathscr{F}} \left(Q^{price}(x), Q^{GHGE}(x) \right) \tag{5}$$

where $\mathscr{F}$ is the feasible set including three types of constraints: nutritional, acceptability and health constraints.

Generally, if the problem is nontrivial, the objective functions are conflicting, that is no single solution exists that simultaneously optimizes each objective. In this case, one has to figure out how to balance priorities and attention must be given to Pareto optimal solutions, that is feasible solutions that cannot be improved in any of the objectives without degrading at least one of the others. These solutions constitute a set known as the Pareto optimal set and the trade−off between objectives can be made within this set, rather than considering the full range of feasible solutions. This set can be computed, for example, scalarizing the problem, that is defining an appropriate sequence of single−objective optimization problems whose optimal solutions are the Pareto optimal solutions of the multi−objective optimization problem. A well known scalarization method is the so called ε−constraint method (Miettinen, 1998) that consists of minimizing one objective when applying upper bounds to all the others. In the present case, the Pareto optimal set of (5) can be computed solving either the following problem:

$$\min_{x \in \mathscr{F}'} Q^{GHGE}(x) \tag{6}$$

where $\mathscr{F}' = \mathscr{F} \cap \{Q^{price} \leq P\}$ with P varying in a suitable range, or

$$\min_{x \in \mathscr{F}''} Q^{price}(x) \tag{7}$$

where $\mathscr{F}'' = \mathscr{F} \cap \{Q^{GHGE} \leq C\}$ with C varying in a suitable range. Note that both the objectives in the above problems are linear function of the binary variables $x^i_{m,d,w}$.

2.1.2. Constraints and feasible set

Nutrition plays a crucial role in health promotion and chronic disease prevention. To this end nutritionists and various medical and governmental institutions provide evidence-based nutrition information and advice for people to help them make healthy choices about food and beverages in their daily lives. This information mainly consists of dietary guidelines (EU DRI, 2017; US DRI, 2004) defining nutrient requirements, recommended nutrient intakes as well as recommended consumption level of some foods (Nishida et al., 2004; WHO, 2015). The nutrients include energy, proteins, carbohydrates, fats and sugars. The dietary patterns recommended in the guidelines allow taking enough of the nutrients essential for good health and help reduce chronic health problems such as heart disease, type 2 diabetes, some cancers and obesity. The core recommendation for an healthy food consumption is to eat foods like, for example, vegetables, fruits, fish and lean meats. They also recommend limiting consumption of red meat and added sugars as well as avoiding consumption of processed meat and alcohol drinking. Moreover, a varied diet, that is a wide range of different recipes, is recommended. In fact, this provides different types and amounts of key nutrients and makes the meals more interesting thus avoiding getting bored with diet. Finally, the diet must be culturally acceptable taking into account as much as possible people's eating habits. This is mainly addressed complying with the structure of the different meals of the day and limiting recipe repetitions in the menu.

2.1.2.1. Nutritional constraints. These constraints consist of reference ranges of energy and nutrient intakes for each meal, depending on the type of meal, for the whole day and for an entire week. These recommendations can then be expressed as box constraints over the feature quantities $Q^f_{m,d,w}(x)$, $Q^f_{d,w}(x)$ and $Q^f_w(x)$. Hence, according to (1), (2) and (3), the constraints are linear functions of the binary variables $x^i_{m,d,w}$ as follows:

$$lb^f_m \leq \sum_{i \in I} x^i_{m,d,w} \cdot Q^f_i \leq ub^f_m \tag{8}$$

for any m, d and w,

$$lb^f_d \leq \sum_{m \in M} \sum_{i \in I} x^i_{m,d,w} \cdot Q^f_i \leq ub^f_d \tag{9}$$

for any d and w, and

$$lb^f_w \leq \sum_{d \in D} \sum_{m \in M} \sum_{i \in I} x^i_{m,d,w} \cdot Q^f_i \leq ub^f_w \tag{10}$$

for any w. The lower and upper bounds lb^f_m, ub^f_m, lb^f_d, ub^f_d, lb^f_w and ub^f_w can be derived from dietary reference values (EU DRI, 2017; US DRI, 2004). Constraints (8), (9) and (10), for all $f \in F$, define a subset $\mathscr{N}$ of X.

2.1.2.2. Acceptability constraints. A common eating pattern is three meals − breakfast, lunch, and dinner − per day, with snacks between meals. Each meal $m \in M$ can contain only a subset of the available recipes and, depending on the country habits, has a defined structure composed of N_m categories: for example, in the mediterranean area, typical lunches and dinners are composed of a first course, a second course, a side dish, fruit and bread (i.e. $N_m = 5$ when $m = lunch$). Each one of these categories corresponds to a set of indexes $I_m^h \subset I$, with $h \in \{1, \ldots, N_m\}$. As a consequence, the constraints on the composition of each meal m in any day d of any week w, can be expressed as follows:

$$\sum_{i \in I} x^i_{m,d,w} = N_m, \qquad \sum_{i \in I_m^h} x^i_{m,d,w} = 1 \tag{11}$$

for all $h \in \{1, \ldots, N_m\}$.

Further acceptability constraints follow from the need to propose a varied and attractive menu. To this purpose, each recipe may be served within a minimum and a maximum number of times a day, a week and in the whole menu. These recommendations can then be expressed as box constraints over these rates, denoted as $R^i_{d,w}(x)$, $R^i_w(x)$ and $R^i(x)$ for any $i \in I$. They can be computed as follows:

$$R^i_{d,w}(x) = \sum_{m \in M} x^i_{m,d,w}, \tag{12}$$

$$R^i_w(x) = \sum_{d \in D} R^i_{d,w}(x) = \sum_{d \in D} \sum_{m \in M} x^i_{m,d,w} \tag{13}$$

and

$$R^i(x) = \sum_{w \in W} R^i_w(x) = \sum_{w \in W} \sum_{d \in D} \sum_{m \in M} x^i_{m,d,w} \tag{14}$$

Hence, for any i, according to (12), (13) and (14), acceptability constraints are linear functions of the binary variables $x^i_{m,d,w}$ as follows:

$$lb^i_d \leq \sum_{m \in M} x^i_{m,d,w} \leq ub^i_d \tag{15}$$

for any d and w,

$$lb^i_w \leq \sum_{d \in D} \sum_{m \in M} x^i_{m,d,w} \leq ub^i_w \tag{16}$$

for any w, and

$$lb^i \leq \sum_{w \in W} \sum_{d \in D} \sum_{m \in M} x^i_{m,d,w} \leq ub^i \tag{17}$$

The lower and upper bounds lb^i_d, ub^i_d, lb^i_w, ub^i_w, lb^i and ub^i can be chosen in order to have a varied menu (Innes-Farquhar, 2000). Constraints (11), (15), (16) and (17), for all $i \in I$, define a subset $\mathscr{A}$ of X.

2.1.2.3. Health constraints. These recommendations consist in limiting or avoiding the consumption of some food groups and increasing that of others. To take into account such a kind of recommendations, recipes must be further assigned to a set G of specific groups such as fruit, vegetables, red meat, processed meat, …. Each of these groups is defined by a set of indexes $I_g \subset I$, with $g \in G$. Subset I_g addresses all the recipes containing a significant quantity of the item defining group g; as an example, beef burger and veal cutlet recipes are part of the “red meat” food group.

Health recommendations can then be expressed as box constraints over the daily, weekly and menu rates of each group of recipes. The rates of each group are obtained summing up the daily, weekly and menu rates given in (12), (13) and (14) for the indexes in the group itself. Hence, for any $g \in G$, the constraints are the following:

$$lb^g_d \leq \sum_{i \in I_g} \sum_{m \in M} x^i_{m,d,w} \leq ub^g_d \tag{18}$$

for any d and w,

$$lb^g_w \leq \sum_{i \in I_g} \sum_{d \in D} \sum_{m \in M} x^i_{m,d,w} \leq ub^g_w \tag{19}$$

for any w, and

$$lb^g \leq \sum_{i \in I_g} \sum_{w \in W} \sum_{d \in D} \sum_{m \in M} x^i_{m,d,w} \leq ub^g \tag{20}$$

The lower and upper bounds lb^g_d, ub^g_d, lb^g_w, ub^g_w, lb^g and ub^g can be derived from World Health Organization dietary guidelines (Nishida et al., 2004; WHO, 2015). Constraints (18), (19) and (20), for all $g \in G$, define a set $\mathscr{H} \subset X$.

2.1.2.4. Feasible set. The feasible set $\mathscr{F}$ is defined by all $x \in X$ that satisfy the nutritional, acceptability and health constraints described above, i.e.

$$\mathscr{F} = \mathscr{N} \cap \mathscr{A} \cap \mathscr{H}$$

Some remarks are in order in the definition of $\mathscr{F}$. In fact, some constraints are strictly interconnected: for instance, the quantity constrained by (9) for any d, w and f, is the sum over m of the quantities constrained by (8) for the same values of d, w and f. Hence, the two sets of constraints are unfeasible if

$$\sum_{m \in M} ub^f_m < lb^f_d \qquad or \qquad \sum_{m \in M} lb^f_m > ub^f_d$$

The first condition, for example, simply means that even if, for a given feature, the maximum allowed for each meal is given, the minimum value that must be provided in one day would not be obtained. On the other hand, if

$$\sum_{m \in M} ub^f_m < ub^f_d \qquad and \qquad \sum_{m \in M} lb^f_m > lb^f_d$$

then the daily constraints (9) are inactive and can be suppressed. Both the constraints being active corresponds to allow a larger intake variation on the single meal while keeping the daily intake closer to the recommended average.

The same kind of interconnection does exist between nutritional constraints (9) and (10). Moreover, when considering the sets of acceptability and health constraints, these interconnections arise within each set and between the two sets as well. In fact, for example, the quantities constrained by (16) and (18) are the sums of those constrained by (15) over $d \in D$ and over $i \in I_g$, respectively.

The feasible set $\mathscr{F}$ is defined by linear relationships on the binary optimization variables $x^i_{m,d,w}$. Therefore, problems (6) and (7) have a linear objective function subject to linear constraints so that they results to be 0−1 integer linear programming problems.

2.2. Materials

The case study considered in this paper is that of designing a two weeks cycle menu for nursing homes. The set of possible recipes is retrieved from a national sample of Italian nursing home menus by extracting different recipes along with the weight of their ingredients and consists of 143 recipes.

The features considered are *energy, proteins, fats, carbohydrates, sugars, price* and *GHGE*. Energy and nutrient contents of recipes are calculated from their ingredients using the database of the French Agency for Food, Environmental and Occupational Health & Safety (CIQUAL, 2017). GHGE values are obtained from the Carbon Scope Data LCI database using the CleanMetrics ™food carbon emission calculator (CleanMetrics, 2011). The cost of recipes is determined collecting the prices of their ingredients from a sample of local stores considering the mean value price while ignoring prices on specials.

2.2.1. Nutritional constraints

To tackle nutritional recommendations, a diet consisting of breakfast, morning and afternoon snacks, lunch, and dinner, equivalent to 1,800 kcal/day is considered. Nutritionists recommend a distribution of the daily energy content of at least 10% from breakfast, about 75% from lunch and dinner and the remaining 15% from snacks (Hermengildo et al., 2016). In this case study, snacks are chosen to be the same for each day. They include a fruit yogurt pot (125 g), a cup of tea and four–five biscuits (40 g) distributed between morning and afternoon. They provide about 290 kcal, that is about 15% of daily energy content. Consequently, the menu consists of determining the recipes composing breakfast, lunch and dinner for a cycle menu of two weeks. Breakfast is constrained to provide at least 200 kcal, that is greater than 10% of daily energy content.

Proteins, fats and carbohydrates provide the most of energy according to percentage ranges $10-35\%$, $20-35\%$, $45-60\%$, respectively, as recommended by (LARN, 2014). Moreover, dietary guidelines recommend daily sugar intake to be less than 20% of energy. In this case study, proteins, fats and carbohydrates are constrained to have an average daily content equal to 19%, 25% and 56% of daily energy content, respectively. Reference daily ranges are then obtained considering the distribution spread of energy and nutrient values over the set of recipes: they result in $1,800\pm 10\%$ kcal for energy, $86\pm 20\%$ g for proteins, $50\pm 20\%$ g for fats and $269\pm 10\%$ g for carbohydrates. The daily content of sugars must be less than 93 g.

These ranges define the bounds lb_d^f and ub_d^f in inequalities (9). The minimum value of energy at breakfast defines the bound lb_m^f in inequality (8).

In summary, inequalities (8) are considered only for energy at breakfast while inequalities (9) are considered for energy, proteins, fats, carbohydrates and sugars. Inequalities (10) are not considered in this case study.

2.2.2. Acceptability constraints

The recipes are divided in different categories corresponding to the structure of breakfast, lunch and dinner. Breakfasts must contain exactly one recipe from the categories *cereals* (cornflakes, biscuits, rusks, …), *beverages* (milk, coffee, tea, juice, …) and *sweeteners* (sugar, honey, jam, …). On the other hand, lunches and dinners, must contain exactly one recipe in the categories *first courses* (pasta, soup, rice, …), *second courses* (eggs, meat, fish, …), *side dishes* (salad, tomatoes, carrots, …), *fruits* and *bread*. These meal structures define equalities (11). Since the mid−morning and afternoon snacks are fixed, then no snack categories are considered.

To obtain a varied menu, recipes corresponding to first and second courses cannot be served more than once in the entire menu. Hence, $lb^i = 0$ and $ub^i = 1$ in inequalities (17), for recipes in such categories. As a consequence, inequalities (15) and (16) are useless. On the other hand, since there is a limited number of side dishes that can be served, then recipes in this category need to appear more than once in the whole menu. Inequalities (15), (16) and (17) are then defined in such a way that any side dish can be provided at most once a day, twice a week and three times in the whole menu. Same arguments hold for recipes composing breakfasts.

2.2.3. Health constraints

The World Health Organization (WHO, 2015) discourages the consumption of animal products, especially red and processed meat and recommends increasing that of plant-based foods, and in particular that of fruits, vegetables and legumes. Following these guidelines the recipes are divided in some groups, that is *pasta, rice, soup, red meat, white meat, processed meat, fish, eggs, cheese, and legumes*[3] and their daily, weekly and total rates are defined. This corresponds to set upper and lower bounds in inequalities (18), (19) and (20). For example, recipes containing fish can be served at most once a day, and between two and three times a week. Moreover, they must be served at least five times in the whole menu. Therefore, $lb_d^{fish}=0$, $ub_d^{fish}=1$, $lb_w^{fish}=2$, $ub_w^{fish}=3$, $lb^{fish}=5$ and $ub^{fish}=6$. On the contrary, a limited consumption of red meat is obtained imposing that it can be served exactly once in a week. This corresponds to set $lb_d^{red\ meat}=0$, $ub_d^{red\ meat}=1$, $lb_w^{red\ meat}=1$ and $ub_w^{red\ meat}=1$. Note that inequalities (20) are useless for this group. Similar arguments hold for recipes composing the other groups.

3. Results and discussion

First of all, the minimum GHGE and the minimum price of any feasible menu, that is a menu satisfying the nutritional, acceptability and health constraints, is determined. The minimum GHGE is obtained by solving the following problem:

$$\min_{x\in\mathscr{F}} Q^{GHGE}(x)$$

and amounts to $Q_{min}^{GHGE}=20,765.7$ g of CO_{2eq} per person. Similarly, the minimum price is obtained by solving the following problem:

$$\min_{x\in\mathscr{F}} Q^{price}(x)$$

and amounts to $Q_{min}^{price}=75.15$ € per person. In general, the menu attaining either Q_{min}^{GHGE} or Q_{min}^{price} may not be unique so that, for example, there may be several menus that cost Q_{min}^{price} but produce different GHGE. This can be verified by solving the following optimization problems:

$$\min_{x\in\mathscr{F}'''} Q^{GHGE}(x), \qquad \max_{x\in\mathscr{F}'''} Q^{GHGE}(x)$$

where $\mathscr{F}'''=\mathscr{F}\cap\{Q^{price}=Q_{min}^{price}\}$. The results show that there is more than one menu with minimal price and that its GHGE is within 26,427.2 and 27,182.2 g per person. Any of such a menu corresponds to a point on the vertical segment $A-A'$ in Fig. 1 where each feasible menu is represented by a point corresponding to its price and the GHGE needed to serve it.

Analogously, there might be menus with different price producing minimal emissions Q_{min}^{GHGE}. This can be verified by solving the following optimization problems:

$$\min_{x\in\mathscr{F}''''} Q^{price}(x), \qquad \max_{x\in\mathscr{F}''''} Q^{price}(x)$$

[3] Note that side dishes are all vegetable foods so that it is not necessary to introduce a vegetable group.

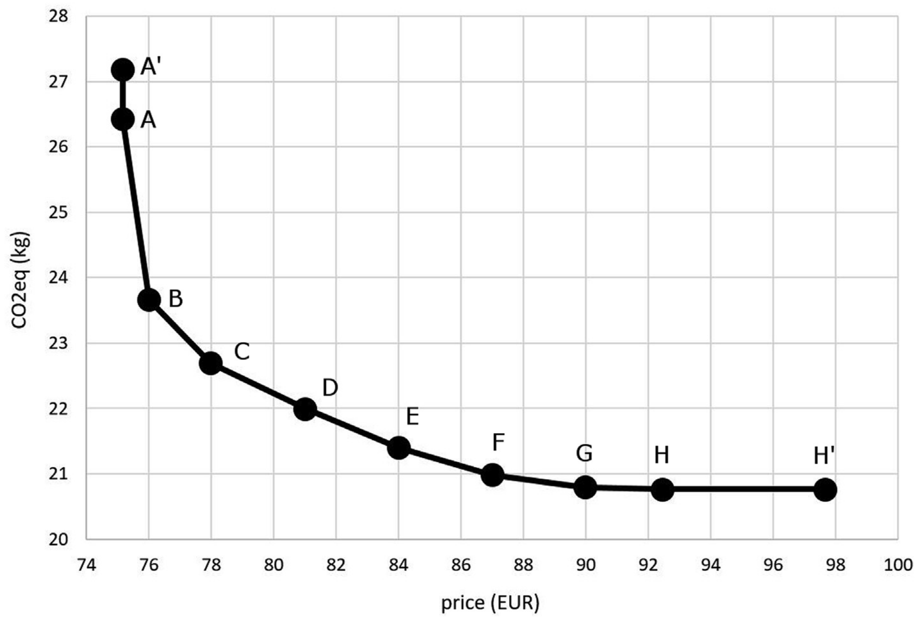

Fig. 1. Relation between the price and GHGE of optimal menus.

where $\mathscr{F}'''' = \mathscr{F} \cap \{Q^{GHGE} = Q^{GHGE}_{min}\}$. The results show that there is more than one menu producing minimal emissions with a price within 92.43 and 97.64 € per person. Any of such a menu corresponds to a point on the horizontal segment $H-H'$ in Fig. 1.

These two experiments show that there does not exists a solution that simultaneously optimizes price and GHGE. Therefore, the two objective functions are conflicting: environmental friendly menus are more expensive, and vice versa. Then, in the case of this study, the Pareto optimal solutions have to be computed by solving problem (6) with $75.15 \leq P \leq 92.43$.

Table 1 reports the price and the minimal GHGE corresponding to the solution of the above problem for some selected values of the upper bound *P*.

The values of Table 1 correspond to the points *A*, *B*, *C*, *D*, *E*, *F*, *G* and *H* on the curve in Fig. 1.

It is worth noting that the same solutions can be obtained by solving problem (7) with $20,765.7 \leq C \leq 26,427.2$.

The curve in Fig. 1 represents the Pareto optimal set of the multi−objective optimization problem (5) and represents the trade−off between price and GHGE over feasible menus. All the Pareto optimal menus are considered equally good from a nutritional, acceptability and health point of view. Moreover, they are mainly equivalent also with respect to the distribution of energy, proteins, fats and carbohydrates daily contents over the 14 days of the menu. This is clearly shown in Fig. 2 where the box plots of the distributions of energy and nutrients content over the days of the menu are depicted for the menus corresponding to the solutions reported in Table 1.

Table 1
Price and GHGE values for menus solving the optimization problem (6) for different values of *P*.

P (€)	price (€)	CO_{2eq} (g)	point
75.15	75.15	26,427.2	A
76	76.00	23,662.3	B
78	77.97	22,692.2	C
81	81.00	21,996.8	D
84	84.00	21,397.9	E
87	86.99	20,983.7	F
90	89.96	20,795.4	G
92.43	92.43	20,765.7	H

The distributions of sugar daily content for the menus in Table 1 are depicted in Fig. 3. As opposite to the other nutrients, the sugar distributions differ more one to another since sugars content has a more tolerant constraint.

Table 1 shows that the prices of the menus solving the optimization problem (6) are always very close to the maximal allowable price *P*, that is the price constraint boundary. This depends on the fact that the number of available recipes is sufficiently rich to provide recipes with small different prices but nearly equivalent from a nutritional point of view. In fact, menus with a small difference in price are substantially the same, that is only few recipes are substituted with others. Table 2 reports the number of recipes shared by each pair of optimal menus over the 210 total recipes composing each one. Any row clearly shows that the number of common recipes decreases as the difference in price increases.

As a consequence, the relation between GHGE and price is quite smooth, as Fig. 1 clearly shows. Moreover, the environmental impact of the menu is in a kind of inverse proportion to the menu price. If the quality of a menu is evaluated only in terms of nutritional and health characteristics and acceptability, then any feasible menu obtained with the proposed model, including any Pareto optimal menu, is equally good. Hence, if price priority is chosen, then menus corresponding to points in the left hand side of the curve in Fig. 1 will be considered. In particular, the best choice will correspond to a menu at minimum price corresponding to a point on the vertical segment $A-A'$ of the curve. This is the usual choice of nursing home management that wants to reduce costs while ensuring residents to receive a varied and healthy diet that meets their nutritional needs. A more sustainable choice should instead balance economic and environmental issues, as suggested by the UN Food and Agricultural Organization (FAO, 2010). The present study shows that this can be fruitfully made. To this end, let us consider a menu at minimum price and the set of Pareto optimal menus, corresponding to points on the curve. Since the curve is very steep on the left, that is for high values of GHGE, then a small

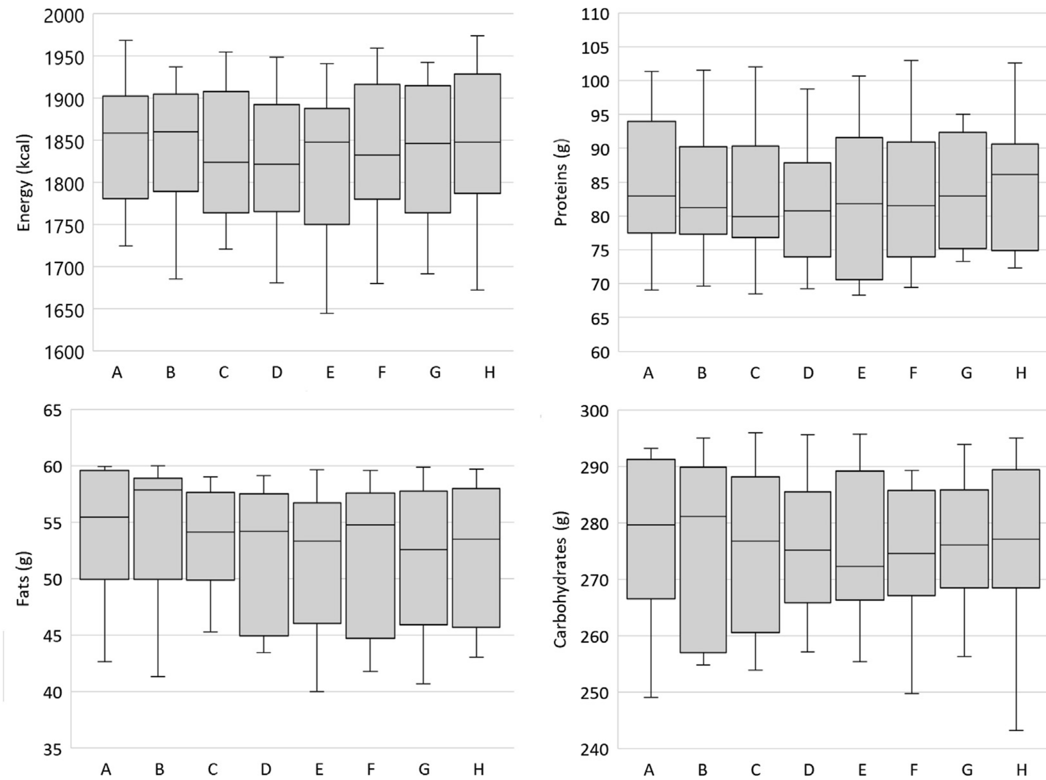

Fig. 2. Box plots of daily content distributions of energy, proteins, fats and carbohydrates for the menus in Table 1.

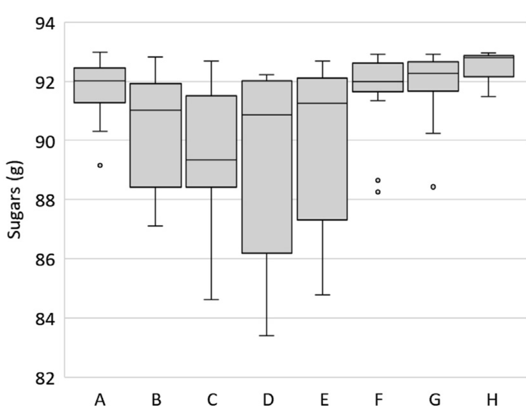

Fig. 3. Box plots of daily content distributions of sugar for the menus in Table 1.

increase of the menu price will determine a great decrease of the GHGE produced to provide the menu itself. Fig. 4 shows the price

Table 2
Numbeenus.

		A	B	C	D	E	F	G	H
		75.15	76.00	77.97	81.00	84.00	86.99	89.96	92.43
A	75.15	210	200	190	188	182	171	160	159
B	76.00	–	210	200	197	191	179	168	163
C	77.97	–	–	210	205	199	185	176	171
D	81.00	–	–	–	210	203	188	177	173
E	84.00	–	–	–	–	210	195	184	180
F	86.99	–	–	–	–	–	210	198	194
G	89.96	–	–	–	–	–	–	210	204
H	92.43	–	–	–	–	–	–	–	210

percentage increase and the GHGE percentage decrease for the menus corresponding to points *B*, *C*, *D* and *E* with respect to the menus corresponding to a point on the segment $A - A'$.

For instance, the choice of the menu corresponding to point *B* results in a reduction of about 12 percent on GHGE but costs only 1 percent more, while that of the menu corresponding to point *C* results in a reduction of about 15 percent of GHGE but costs less than 4 percent more. If all the nursing homes in Italy would adopt this tradeoff solution, for example to serve a menu reducing GHGE of 15 percent, the amount of gas emissions avoided would be about equal 30,000 tonnes of CO_{2eq} per year. This can be computed considering that the number of people in nursing homes in Italy is about equal to 287,000, as indicated by the National Institute of Statistics (ISTAT, 2011). In conclusion, this study suggests that the promotion of a healthy food consumption pattern that balances economic and environmental issues, in any facility with service canteen, would result in a considerable reduction of greenhouse gas emissions with an affordable extra cost.

3.1. Advantages, limitations and future research

The proposed method has some key features quite significant from a technical point of view. The model is capable to cope with a data–base of recipes of increased size (scalability). In other words, more recipes and constraints can be added without affecting the structure of the model. Moreover, recipes and constraints can be easily adapted to deal with special diets for health conditions such as diabetes and celiac disease or food intolerance and allergies. Further, more objective goals describing environmental impact can be considered besides GHGE: for example, water consumption, food transport and packaging. On the other hand, scalability of the model significantly impacts on the number of variables and constraints, thus delivering optimization problems with increasing

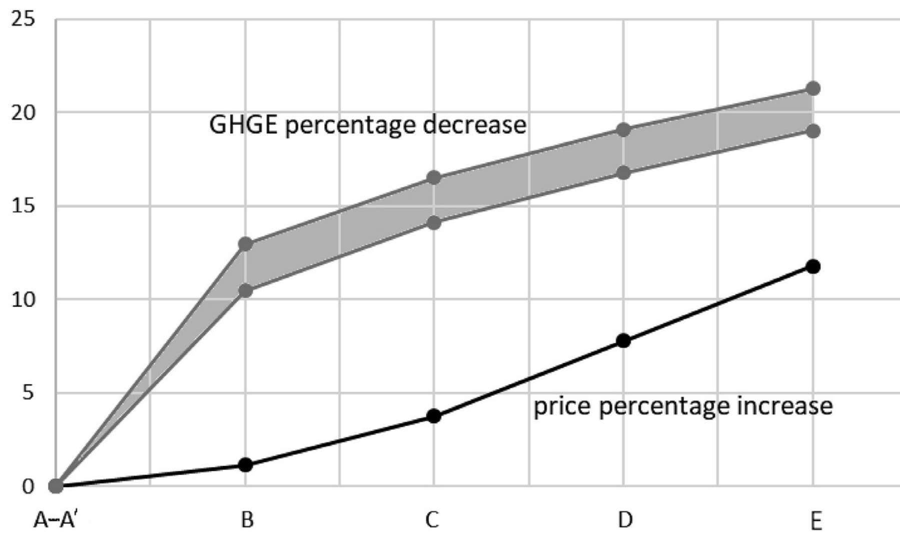

Fig. 4. Price percentage increase and the GHGE percentage decrease for the menus corresponding to points *B*, *C*, *D* and *E* with respect to the menus corresponding to a point on the segment *A*–.*A*′

size. This may produce a very long computation time to solve the optimization problems but a more serious limitation that may occur is the downsize of the set of feasible solutions when more constraints are considered. In particular, as discussed in Section 2.1.2, some effort is needed to make all the constraints consistent since, in general, they regard different features such as nutrient contents, meals composition and recipes allowed repetitions. A final limitation of the current study is that it considers fixed size recipes. This allows to find feasible solutions only for suitable large reference daily ranges for energy and nutrients. In fact, as pointed out in Section 2.2, these ranges mainly depend on the distribution spread of energy and nutrient values over the set of recipes and may not be adequate to nutritionist requirements. This is the key issue to be tackled in future research. Two different approaches can be followed with complementary pros and cons. The first one consists of adding a continuous variable for each recipe corresponding to its size. In this case a mixed–integer optimization problem is obtained that results in a seriously more complex problem to solve. Moreover, the solution would provide recipes with impractical size, that is difficult to prepare. On the other hand, smaller reference daily ranges for energy and nutrients could be considered to better comply with nutritionist advices. The second approach consists of considering only appropriate modified recipe serving sizes, like half portion and full portion. This increases the number of binary variables but the nature of the optimization problem remains unchanged. Moreover, the optimal solution corresponds to recipes with practical size. In this case, reference daily ranges can be reduced even if they cannot be finely tuned as in the previous approach.

4. Conclusions

The main scientific contribution of this study is that of providing a multi–objective optimization methodology able to define a healthy, nutritionally adequate and varied menu while making a trade–off between its economic and environmental impact. The method relies on a model that allows to choose the composition and the sequence of daily meals using items within a given set of different recipes. Hence, the proposed methodology can be used to design not just food plans, as usually obtained using linear programming techniques, but a true menu consisting of real dishes and their scheduling. The data needed to implement the model are the nutritional values of each recipe, its price and the quantity of greenhouse gases emitted in the atmosphere to produce its ingredients. These data can be easily retrieved from available databases. The methodology can be directly applied to define menus for establishments such as schools, hospice, hospitals and private companies with canteens. It guarantees nutrients to be in prescribed reference ranges, recommended levels of consumption of some selected food groups and meals structured according to people eating habits. In this paper, the proposed methodology is applied to the case of a full board menu of a nursing home for a period of two full weeks. The conflicting objectives considered are the price and the GHGE of the menu. The set of optimal menus that represent the trade–off between the two goals, is determined by solving a sequence of single-objective optimization problems having GHGE as goal and different price upper bounds. It turns out that price and GHGE are in a kind of inverse proportion and that a sustainable choice balancing economic and environmental issues can be fruitfully made. In fact, a considerable reduction of greenhouse gas emissions is possible with a very small extra cost.

References

Benvenuti, L., De Santis, A., Santesarti, F., Tocca, L., 2016. An optimal plan for food consumption with minimal environmental impact: the case of school lunch menus. J. Clean. Prod. 129, 704–713.
CIQUAL, 2017. French food composition table. https://ciqual.anses.fr/.
CleanMetrics, 2011. Food Carbon Emissions Calculator. CleanMetric™. http://www.foodemissions.com/foodemissions/Calculator.aspx.
DGAC SR, 2015. Dietary Guidelines Advisory Committee. Scientific Report of the 2015. US Department of Agriculture and US Department of Health and Human Services, Washington (DC), 2015.
Donati, M., Menozzi, D., Zighetti, C., Rosi, A., Zinetti, A., Scazzina, F., 2016. Towards a sustainable diet combining economic, environmental and nutritional objectives. Appetite 106, 48–57.
EU DRI, 2017. Overview on Dietary Reference Values for the EU Population as Derived by the EFSA Panel on Dietetic Products. Nutrition and Allergies.
FAO, 2010. Sustainable diets and biodiversity. Directions and solutions for policy, research and action. In: Burlingame, B., Dernini, S. (Eds.), Proceedings of the International Scientific Symposium Biodiversity and Sustainable Diets United against Hunger. FAO Headquarters, Rome.
Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling Climate Change through Livestock: a Global Assessment of Emissions Ad Mitigation Opportunities. FAO Headquarters, Rome.
Hermengildo, Y., López-García, E., García-Esquinas, E., Pérez-Tasigchana, R., Rodríguez-Artalejo, F., Guallar-Castillón, P., 2016. Distribution of energy intake

throughout the day and weight gain: a population-based cohort study in Spain. Br. J. Nutr. 115 (11), 2003–2010.
Innes-Farquhar, A., 2000. Catering in nursing and residential homes. Nurs. Resid. Care 2 (12), 588–590.
ISTAT, 2011. Health and social–assistance facilities (in Italian). http://dati.istat.it/Index.aspx?DataSetCode=DCIS_PRESIDI1/.
LARN, 2014. Italian Population Reference Intake Levels for Energy and Nutrients (In Italian). IV Review. SINU.
Macdiarmid, J.I., Kyle, J., Horgan, G.W., Loe, J., Fyfe, C., Johnstone, A., McNeill, G., 2012. Sustainable diets for the future: can we contribute to reducing greenhouse gas emissions by eating a healthy diet? Am. J. Clin. Nutr. 96 (3), 632–639.
Masset, G., Monsivais, P., Maillot, M., Darmon, N., Drewnowski, A., 2009. Diet optimization methods can help translate dietary guidelines into a cancer prevention food plan. J. Nutr. 139, 1541–1548.
Mertens, E., vant Veer, P., Hiddink, G.J., Steijns, J.M., Kuijsten, A., 2017. Operationalising the health aspects of sustainable diets: a review. Public Health Nutr. 20, 739–757.
Miettinen, K., 1998. Nonlinear Multiobjective Optimization. International Series in Operations Research & Management Science, vol. 12. Springer.
Nelson, M.E., Hamm, M.W., Hu, F.B., Abrams, S.A., Griffin, T.S., 2016. Alignment of healthy dietary patterns and environmental sustainability: a systematic review. Adv. Nutr. 7 (6), 1005–1025.
Nishida, C., Uauy, R., Kumanyika, S., Shetty, P., 2004. The Joint WHO/FAO Expert Consultation on diet, nutrition and the prevention of chronic diseases: process, product and policy implications. Public Health Nutr. 7 (1A), 245–25.
Ribal, J., Fenollosa, M.L., Garcia-Segovia, P., Clemente, G., Escobar, N., Sanjuan, N., 2016. Designing healthy, climate friendly and affordable school lunches. Int. J. Life Cycle Assess. 21 (5), 631–645.
UNEP, 2012. The Critical Role of Global Food Consumption Patterns in Achieving Sustainable Food Systems and Food for All. Technical Report. United Nations Environment Programme, 2012.
UN, 2015. Transforming Our World: the 2030 Agenda for Sustainable Development. United Nations. https://sustainabledevelopment.un.org/post2015/transformingourworld.
US DRI, 2004. Dietary Reference Intakes (DRIs): Recommended Intakes for Individuals, Food and Nutrition Board. Institute of Medicine, National Academies, USA.
van Dooren, C., Tyszler, M., Kramer, G., Aiking, H., 2015. Combining low price, low climate impact and high nutritional value in one shopping basket through diet optimization by linear programming. Sustainability 7, 12837–12855.
van Dooren, C., 2018. A review of the use of linear programming to optimize diets, nutritiously, economically and environmentally. Front. Nutr. 5, 48.
Vermeulen, S.J., Campbell, B.M., Ingram, J.S.I., 2012. Climate change and food systems. Annu. Rev. Environ. Resour. 37, 195–222.
WHO, 2015. Healthy Diet, Fact Sheet N. 394. Updated January.
Wilson, N., Nghiem, N., Ni Mhurchu, C., Eyles, H., Baker, M.G., Blakely, T., 2013. Foods and dietary patterns that are healthy, low-cost, and environmentally sustainable: a case study of optimization modeling for New Zealand. PLoS One 8 (3).