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

Luca Benvenuti[*] Alberto De Santis[*] Andrea Di Sero
Nicola Franco[†]

May 20, 2019

Abstract

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, the relation between the environmental impact and the price of diets is addressed. To this aim, the case of cycle menus for nursing homes is investigated by means of an optimization model able to allocate pre-specified recipes over the meals of the menu. As a first result, the case study shows that the menu's environmental impact is generally in inverse proportion to its price. Hence, environmental friendly food consumption is more expensive. Nevertheless, it is possible to obtain a menu with an environmental impact close to the lowest possible while reducing significantly its price. This is shown by determining the exact relation between these two competing goals that is obtained through the solution of a set of optimization problems in which environmental impact and menu price exchange their role as objective function and constraint.

Keywords: Food consumption pattern; Environmental sustainability; Economic sustainability.

1 Introduction

The global food system is a complex mix of production, processing, storage and transportation activities that move products from field-to-fork. Food production is driven by policy choices and consumer demand (Blackstone et al., 2018) which in turn depends on dietary habits and costs. On the other hand, firms' short-term profits are usually the main driver of policy choices (UNEP, 2011) and this causes the production to be a resource-inefficient series of tasks. Production should instead be implemented by balancing economic, environmental, and social issues in the

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[*] Department of Computer, Control, and Management Engineering - Sapienza University of Rome, Via Ariosto 25, 00185 Roma, Italy.

[†] Italian Association for Dietetics and Clinical Nutrition

present generation and for future ones (Lozano et al., 2015). The same focus should be ensured when considering consumer demand. Indeed, 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; while optimizing natural and human resources." As suggested in (UNEP, 2015), diets sustainability can be pursued by:

- Reducing material/energy intensity of current economic activities and reducing emissions and waste from extraction, production, consumption and disposal.
- Promoting a shift of consumption patterns towards groups of goods and services with lower energy and material intensity without compromising quality of life.

Following these suggestions, the aim of this study is that of defining a healthy food consumption pattern finding a tradeoff between economic and environmental impacts. The promotion of this pattern may be accomplished by planning appropriate scheduled menus in all the facilities with service canteens, such as schools, hospices, hospitals, companies, chain restaurants or other individual establishments. In this paper a model is developed that allows to define a consumption pattern by allocating recipes, from a given set, in the meals of a cycle menu while minimizing either greenhouse gas emissions (GHGEs) or price[1]. The model takes into account factors of different nature:

- (Nutritional issues) The meals have to provide an appropriate content of energy and nutrients. The appropriate contents can be derived from dietary reference guidelines provided by international/local authorities (EU DRI, 2017; US DRI, 2004) defining minimal and maximal values for total energy, proteins, total fat, carbohydrates, sugar, fiber, and sodium for each meal, day and week;
- (Acceptability issues) Each meal, either breakfast, lunch, dinner and snacks, must have a defined structure, depending on the country habits.[2] Moreover, in order to obtain a varied menu, different meals have to be provided each day and each recipe may be served at most for a given number of times in a week and in the whole menu;
- (Health issues) To achieve an healthy diet, the World Health Organization (Nishida et al., 2004) recommends a given range of consumption for some food categories. For example, a limited consumption of red meat and an increased consumption of vegetables is advisable.

In the proposed model, the variables are binary and denote the presence/absence of each recipe in each meal so that a menu consists in assigning values to such variables while satisfying the above issues. This problem is solved by minimizing an objective function, such as the amount of GHGEs needed to provide the whole menu or its price, subject to the constraints given by

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[1] GHGEs here considered consist of those resulting from the life cycle assessment at farm gate and are calculated as carbon dioxide equivalent (CO_{2eq}).

[2] 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.

the nutrition, acceptability and health issues. Since both the constraints and the objective are linear functions of the variables, then the problem consists in a 0–1 integer linear programming problem with both equality and inequality linear constraints. Indeed, linear programming techniques have been applied in (Macdiarmid et al., 2012), (Masset et al., 2009) and (Wilson et al., 2013) in order to obtain healthy diets with reduced environmental impact. These works generally obtain food plans that best resemble current eating habits while meeting nutrition and/or cost constraints. Only in (Macdiarmid et al., 2012) a sample weekly menu is proposed in order to test whether the types and quantities of the optimal food plan could be combined into a realistic diet. This menu is obtained by supervised iterative attempts. The procedure proposed in this paper, instead, is completely unsupervised and directly provides realistic menus.

The model presented in this paper is an extension of that defined in (Benvenuti et al., 2016) that considered a single–lunch menu for school canteens. Moreover, in the present work, two targets are considered, that is GHGEs and price of the menu and the relation between these two targets is studied. This is accomplished by considering one target as objective function and the other as a further constraint. For example, this allow to obtain the menu with minimal GHGEs no more expensive than a given price.

As a case study, a nursing home food service is considered for a cycle menu of two weeks. 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. Energy and nutrients content of the recipes are calculated using the database of the French Agency for Food, Environmental and Occupational Health & Safety (CIQUAL, 2017). GHGEs of each recipe are obtained from the CarbonScopeData LCI database using the CleanMetrics$^{\mathrm{TM}}$food carbon emission calculator (CleanMetrics, 2011). Price 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”.

In order to investigate the relation between the price of a menu and its carbon footprint, the menu which needs the minimum GHGEs to be served as well as the menu with minimum price are firstly determined. Then an optimization model is defined to compute the menu with minimum GHGEs no more expensive than a given price. Decreasing the price allows to unfold the sought relation. These problems are solved using AMPL, an algebraic modeling language for describing and solving large-scale optimization and scheduling type problems.

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, the relation shows that it is possible to tradeoff the menu environmental impact with its economic one, obtaining a menu with a carbon footprint close to the lowest possible while reducing significantly its price.

The paper is organized as follows: in Section 2, methods and materials are presented. In more detail, the optimization model is illustrated by defining the objective function and the problem constraints. Moreover the application of the optimization model to a real world case study, that is a two weeks menu for a nursing home, is addressed. Results are presented and discussed in Section 3. Conclusions are given in Section 4.

2 Methods and Materials

The main goal of this study is to investigate the relation between the environmental and economic impacts of cycle menus served in establishments with canteens service such as schools, hospices, hospitals, ... 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 model

The model describes the scheduling of recipes to be served in a cycle menu taking into account nutrition, acceptability and health issues as well as environmental and economic impacts. The menu must be organized by choosing within a given set of N recipes whose composition and serving size is fixed. This must be scheduled by choosing the sequence of daily meals in order to minimize either the total carbon footprint needed to serve the menu or its price, while providing a varied menu in line with nutritional and health recommendations. The menu can be half board, full board or, in general, it may consider a number of N_M meals within breakfast, lunch, dinner and snacks. Moreover the service can be full week, as for example in hospitals, or workweek, as for company canteens. In general, the menu may consider 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 $M \subseteq \{breakfast, lunch, dinner, snack\}$ 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, a cycle menu is 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 feature f of the recipe i where f takes values in a set F that accounts for the price, the footprint, the energy and various nutrients such as *lipid*, *sugar*, *fiber*, etc ... Then, the features $\{Q^f_{m,d,w}(x)\}$

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

are those corresponding to the meal m of the day d in the week w of the menu. As a consequence, the features $\{Q^f_{d,w}(x)\}$ of all the meals of the day d in the week w are

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

Finally, the features $\{Q^f_w(x)\}$ and $\{Q^f(x)\}$ of all the meals in the w–th week 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 either its price or carbon footprint on a feasible set $\mathcal{F}$ defined by three types of constraints: nutritional constraints, acceptability constraints and health constraints. Hence, the optimization problem to be solved is

$$\min_{x\in\mathcal{F}} \; Q^f(x) \tag{5}$$

where $Q^f(x)$ is as in (4) with f either *price* or *carbon* footprint and is a linear function of the binary variables $x^i_{m,d,w}$.

2.1.2 Nutritional constraints

Nutritionists may recommend different 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 features $Q^f_{m,d,w}(x)$, $Q^f_{d,w}(x)$ 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:

$$lb^f_m \leq \sum_{i\in I} x^i_{m,d,w} \cdot Q^f_i \leq ub^f_m \tag{6}$$

for any m, d and w,

$$lb^f_d \leq \sum_{m\in M}\sum_{i\in I} x^i_{m,d,w} \cdot Q^f_i \leq ub^f_d \tag{7}$$

for any d and w, and

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

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 (6), (7) and (8) define a subset $\mathcal{N}$ of X.

2.1.3 Acceptability constraints

Breakfasts, lunches and dinners, as well as snacks in any day, can be composed with only a subset of the available recipes. Moreover, each kind of meal, 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. $N_m = 5$).

Each one of these categories corresponds to a set of indexes $I^h_m \subset I$, 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:

$$\sum_{i\in I} x^i_{m,d,w} = N_m, \qquad \sum_{i\in I^h_m} x^i_{m,d,w} = 1 \tag{9}$$

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 $R^i(x)$. They can be computed as:

$$R^i_{d,w}(x) = \sum_{m \in M} x^i_{m,d,w}, \tag{10}$$

$$R^i_w(x) = \sum_{d \in D} R^i_{d,w}(x) = \sum_{d \in D} \sum_{m \in M} x^i_{m,d,w} \tag{11}$$

and

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

Hence, for any i, according to (10), (11) and (12), acceptability constraints are linear functions of the binary variables $x^i_{m,d,w}$ as follows:

$$lb^i_d \leq \sum_{m \in M} x^i_{m,d,w} \leq ub^i_d \tag{13}$$

for any d and w,

$$lb^i_w \leq \sum_{d \in D} \sum_{m \in M} x^i_{m,d,w} \leq ub^i_w \tag{14}$$

for any w, and

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

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 (9), (13), (14) and (15) define a subset $\mathcal{A}$ of X.

2.1.4 Health constraints

Various nutrition guides are published by medical and governmental institutions to promote healthful eating among the population (Nishida et al., 2004; WHO, 2015). A healthy diet, in addition to exercise, may lower disease risks, such as obesity, heart disease, type 2 diabetes, hypertension and cancer. The recommendations consist in limiting or avoiding the consumption of some food groups and increasing that of others. For example, public health authorities recommend consuming more plant-based foods, a limited amount of animal products, especially red meat, and avoiding eating processed meet as well as alcohol drinking. To take into account such 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, beefburger and veal cutlet recipes are part of the "red meat" food group.

Health recommendations can then be expressed, for any g, 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 (10), (11) and (12) for the indexes in the group itself. Hence, for any $g \in G$, the constraints are the following:

$$lb^g_d \leq \sum_{i \in I_g} \sum_{m \in M} x^i_{m,d,w} \leq ub^g_d \tag{16}$$

for any d and w,

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

for any w, and

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

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 (16), (17) and (18) define a set $\mathcal{H} \subset X$.

2.1.5 Feasible set

The feasible set is defined by any $x \in X$ that satisfies the nutritional, acceptability and health constraints described above, i.e.

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

Some remarks are in order in the definition of $\mathcal{F}$. In fact, some constraints are strictly interconnected: for instance, the quantity constrained by (7) for any d, w and f, is the sum over m of the quantities constrained by (6) 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 (7) 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 (7) and (8). 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 (14) and (16) are the sums of those constrained by (13) over $d \in D$ and over $i \in I_g$, respectively.

As a final remark, note that the proposed model is completely scalable and can be easily updated with new recipes and constraints. This obviously impacts on the number of variables and constraints, thus delivering optimization problems with increasing size.

2.2 Materials

In Italy, nursing homes with canteen service are in charge to prepare the meals according to a regulation established by local health authorities. The regulation ensures proper nutritional intakes and a healthy diet. In this section the case of a two weeks cycle menu for a nursing home is considered. The menu is obtained by selecting recipes for a given set while complying with nutritional, acceptability and health issues. At the same time, the menu is chosen in such a way to minimize either the environmental impact or its price. 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. It consists of 143 recipes divided in first courses, second courses, side dishes, fruits, different types of bread, and some beverages and sweeteners. 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) and GHGE values are obtained from the CarbonScopeData LCI database using the CleanMetrics$^{\mathrm{TM}}$food carbon emission calculator (CleanMetrics, 2011). Price 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 issues, a diet consisting of breakfast, morning and afternoon snacks, lunch, and dinner, equivalent to 1800 Kcal/day is considered. Nutritionists recommend a distribution of the daily energy content of at least 10% from breakfast, and 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 plain yogurt pot (125 g), a cup of tea, two rusks (18 g) and five-six biscuits (50 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. It generally consists of milk, yogurt or tea, cereals, biscuits or rusks and one fruit.

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 give 19%, 25% and 56% of daily energy content, respectively.

Hence, reference values of the daily content of energy, protein, carbohydrates, fats and sugars are obtained as shown in Table 1.

The allowable variations around the reference (average) values given in Table 1 are obtained considering the distribution spread of energy and nutrient values over the set of recipes. These ranges define the bounds lb_d^f and ub_d^f in inequalities (7). The minimum value of energy at breakfast defines the bound lb_m^f in inequality (6).

In summary, inequalities (6) are considered only for energy at breakfast while inequalities (7) are considered for energy, proteins, fats, carbohydrates and sugars. Inequalities (8) are not considered in this case study.

Energy (Kcal)	$1800 \pm 10\%$
Proteins (g)	$86 \pm 20\%$
Total fats (g)	$50 \pm 20\%$
Carbohydrates (g)	$269 \pm 10\%$
Sugars (g)	< 93

Table 1: Daily average contents and allowable variations of energy and nutrients.

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 *breakfast foods, breakfast beverages, sweeteners*; on the other hand, lunches and dinners, must contain exactly one recipe in the categories *first courses, second courses, side dishes, fruits and bread.* These meal structures define equalities (9).

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 (15), for recipes in such categories. As a consequence, inequalities (13) and (14) are useless. On the other hand, for retired people, there is a limited number of side dishes that can be served. Therefore, recipes in this category need to appear more than once in the whole menu. Inequalities (13), (14) and (15) 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) recommends limiting the consumption of animal products, especially red and processed meat and increasing that of plant-based foods, and in particular that of fruits, vegetables and legumes. Moreover, eating foods of many different groups, helps maintaining a healthy and interesting diet which provides a range of different nutrients to the body. 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 (16), (17) and (18). 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 eaten 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 (18) are useless for this group. Similar arguments hold for recipes composing the other groups.

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

3 Results and discussion

The goal of this study is to define a healthy menu making a tradeoff between economic and environmental impact. This corresponds to unfold the inner relation between the price of a menu and its carbon footprint. To this aim, different optimization models are defined by exchanging the role of price and carbon footprint as objective function and constraint. These problems are then solved using AMPL, an algebraic modeling language for describing and solving large-scale optimization and scheduling type problems.

In more detail, the minimum GHGE is obtained by solving the following optimization problem:

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

The menu corresponding to this solution needs 20765.7 g of CO_{2eq} per person to be served. To determine the range of price of menus with minimal GHGE, the following optimization problems are solved:

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

where $\mathcal{F}' = \mathcal{F} \cap \{Q^{GHGE} = 20765.7\}$. The result shows that the price of a menu with minimal GHGE is within 92.43 and 97.64 € per person. This corresponds to the horizontal segment in Figure 1.

Similarly, the minimum price menu is obtained by solving the following optimization problem:

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

The menu corresponding to this solution costs 75.15 € per person. To determine the range of carbon footprint of menus with minimal price, the following optimization problems are solved:

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

where $\mathcal{F}'' = \mathcal{F} \cap \{Q^{price} = 75.15\}$. The result shows that the GHGE of a menu with minimal price is within 26427.2 and 27182.2 g per person. This corresponds to the vertical segment in Figure 1.

These two experiments show that GHGE and price are conflicting goals, that is decreasing menu prices give more environmental impacting menus, and vice versa. This behavior can be assessed solving a sequence of optimization problems with decreasing price upper bound. The problems can be stated as follows:

$$\min_{x \in \mathcal{F}'''} \; Q^{GHGE}(x) \tag{19}$$

where $\mathcal{F}''' = \mathcal{F} \cap \{Q^{price} \leq P\}$ with $75.15 < P < 92.43$. Table 3 reports the solution of the above problem for some selected values of P.

The values of Table 3 corresponds to the curve in Figure 1. Since the number of available recipes is sufficiently larger than the number of recipes needed to complete the menu, then the optimal solutions have always a price very close to the maximal allowable price, that is the price constraint boundary. The relation between GHGE and price is quite smooth as the figure clearly shows. Moreover, the environmental impact of the menu is in a kind of inverse proportion to the menu price. Notably, the relation is steeper on the left, that is for higher

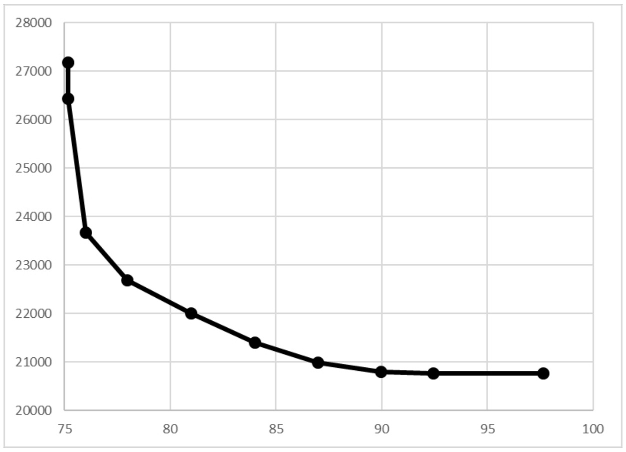

Figure 1: Minimal CO_{2eq} (g) versus menu price (€).

P (€)	price (€)	CO_{2eq} (g)
	75.15	26427.2
76	76.00	23662.3
78	77.97	22692.2
81	81.00	21996.8
84	84.00	21397.9
87	86.99	20983.7
90	89.96	20795.4
	92.43	20765.7

tablePrices vs CO_{2eq}.

GHGE, and slowly decreases when approaching the minimum value of GHGE. Hence, when defining a menu, it is possible to tradeoff the menu environmental impact with its economic one, obtaining a menu with a carbon footprint close to the lowest possible while reducing significantly its price. As a matter of fact, considering the menu with minimal GHGEs and maximal price, a decrease of about 11% in price results only in an increase of 1% in GHGE.

It is worth noting that the same curve can be obtained by solving a complementary sequence of optimization problems with decreasing GHGE upper bound, that is:

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

where $\mathcal{F}'''' = \mathcal{F} \cap \{Q^{GHGE} \leq C\}$ with $20765.7 < C < 26427.2$. In other words, the curve in Figure 1 represents the Pareto frontier of the multi-objective optimization problem having price and GHGE as goals. In fact, the Pareto frontier is the set of menus such that one goal cannot be improved without worsening the other.

Figures 2–6 show the energy and nutrients properties of the optimal menus.

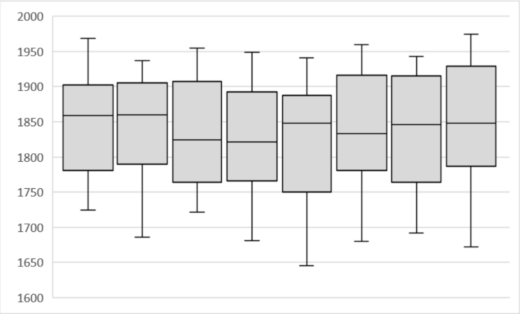

Figure 2: Boxplot of energy content in menus for increasing prices.

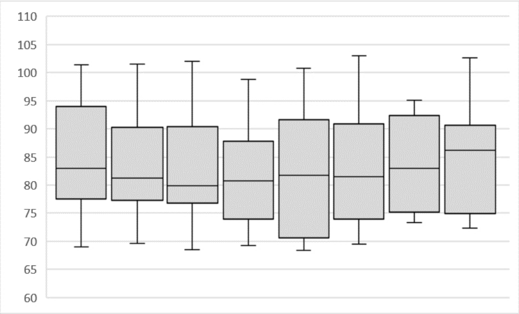

Figure 3: Boxplot of proteins content in menus for increasing prices.

In more detail, the figures display the box-plots of energy and nutrients daily contents over the 14 days of the cycle menus for the price values given in Table 3. Interesting enough,

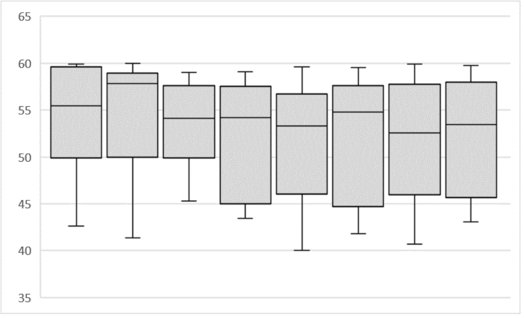

Figure 4: Boxplot of total fats content in menus for increasing prices.

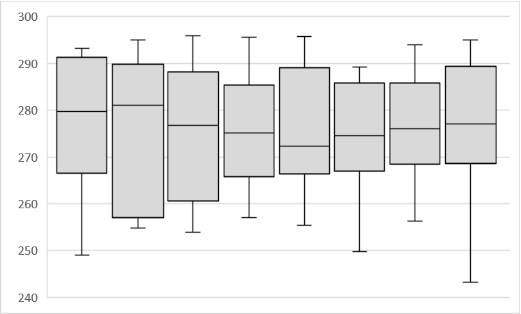

Figure 5: Boxplot of carbohydrates content in menus for increasing prices.

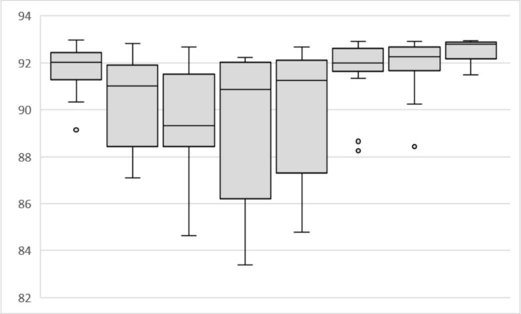

Figure 6: Boxplot of total sugars content in menus for increasing prices.

distributions of features daily content over the cycle menus do not vary significantly with price, apart from sugars content. As a matter of fact, a small decrease in price determines a small change in the menu, that is some recipes are substituted with others while the menu remains substantially the same. 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.

	75.15	76.00	77.97	81.00	84.00	86.99	89.96	92.43
75.15	0	200	190	188	182	171	160	156
76.00	-	0	200	197	191	179	168	163
77.97	-	-	0	205	199	185	176	171
81.00	-	-	-	0	203	188	177	173
84.00	-	-	-	-	0	195	184	180
86.99	-	-	-	-	-	0	198	194
89.96	-	-	-	-	-	-	0	204
92.43	-	-	-	-	-	-	-	0

Table 2: Number of common recipes for optimal menus.

4 Conclusions

A model to define a cycle menu with minimal economic or environmental impact is presented. The model relies on a database of recipes of fixed serving size with known price and carbon footprint. Therefore, menus are obtained by allocating recipes over the courses in order to minimize either the menu price or its carbon footprint. The model can comply with half board or full board menus and the optimal menu is ensured to be healthy, nutritionally adequate and varied. This is accomplished by constraining allowed values for nutrients in appropriate intervals. The size of these intervals must take into account the variability of nutrient values over the given set of recipes. Tighter intervals could be adopted by considering different serving sizes for each recipe. Moreover, the model is completely scalable and can be easily updated with new recipes and health or nutrition requirements.

The case study of a nursing home food service is presented. On this case, the relation between economic and environmental impact of a menu is investigated. To this aim, different optimization problems are solved by exchanging the role of price and carbon footprint as objective function and constraint. These problems are solved using AMPL, an algebraic modeling language for describing and solving large-scale optimization and scheduling type problems.

The result is that GHGE and price are conflicting goals, and in particular they are in a kind of inverse proportion. The precise relation allows to tradeoff the menu environmental impact with its economic one, obtaining a menu with a carbon footprint close to the lowest possible while reducing significantly its price.

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