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Optimizing household food waste: The impact of meal planning, package sizes, and performance indicators

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ABSTRACT

A key reason for the occurrence of household food waste is poor meal planning, which is partly due to inappropriate discrete package sizes at supply level and lack of accounting for unused food at consumer level. Diet modeling has proven to be effective for solving food planning problems. As far as we know, discrete package sizes have not been incorporated in a dietary meal planning model before. The mathematical programming based model formulated in this article proposes meal plans and shopping lists by selecting combinations of recipes based on available retail package sizes such that food waste, costs, GHGE, and nutritional value are optimized. It generates healthy, affordable meal plans with no waste. Moreover, not only food weight but also GHGE should be considered as performance indicator for food waste. This study shows how careful weekly meal planning can help reducing household waste and the carbon footprint of diets.

1. Introduction

One-third of global food production is wasted (Gustavsson et al., 2011). Food waste has several adverse effects, including environmental effects such as soil erosion, deforestation, water and air pollution, as well as greenhouse gas emissions (Schanes et al., 2018). Food waste is a significant contributor to climate change, as food waste is estimated to generate 8% of global greenhouse gasses (FAO, 2013). Food waste in the EU predominantly occurs at the household level, with an average wastage of 98.6 kilograms per person per year (Caldeira et al., 2019; Stenmarck et al., 2016). It is important to note that food wasted at the household level has a larger environmental impact than food wasted upstream in supply chains since a considerable amount of energy has already been invested into food present at household level. This includes, for instance, the transportation, processing, and storage of food (Schanes et al., 2018).

Consumers generally feel guilty about throwing out food and do not waste food intentionally (Watson and Meah, 2012). In fact, consumers consciously and unconsciously negotiate between avoiding food waste and competing priorities, such as food safety, convenience, and time demands (Spang et al., 2019). Studies show that many factors influence food waste, such as poor planning, preparing too much food, confusion about best-before date labels, and time constraints (Boulet et al., 2021; Graham-Rowe et al., 2014; Roodhuyzen et al., 2017; Schanes et al., 2018; Stangherlin and de Barcellos, 2018). As many of these factors are interrelated, it is difficult to exactly quantify the amount of food waste caused by individual factors.

In this paper we focus on meal planning because planning has a substantial influence on all other household food practices: purchasing, storing, preparation and serving, and consumption (Romani et al., 2018). Consumer planning routines include checking inventory levels, making shopping lists, and planning meals, which can help consumers reduce food waste (Stefan et al., 2013). Product package sizes comprise a key factor that complicates the planning stage of food provisioning. Consumers mention large package sizes as among the main reported reasons for food waste (Chan, 2022; Flycatcher, 2019; Williams et al., 2012). The content of packages is often not consumed completely before the best-before date. This suggests that planning food provisioning while taking package sizes into account can reduce food waste. To the best of our knowledge this has not yet been investigated.

Diet modeling has proven to be an effective method to solve food planning problems. So far, this method has mainly been applied to identify nutritious and affordable diets (van Dooren, 2018). Diet modeling uses mathematical optimization techniques to find the optimal combination of foods that fulfills a set of constraints while minimizing or maximizing an objective function (Gazan et al., 2018). For instance, in traditional diet optimization approaches the cost of a diet is minimized while ensuring that all nutrient requirements are fulfilled. More

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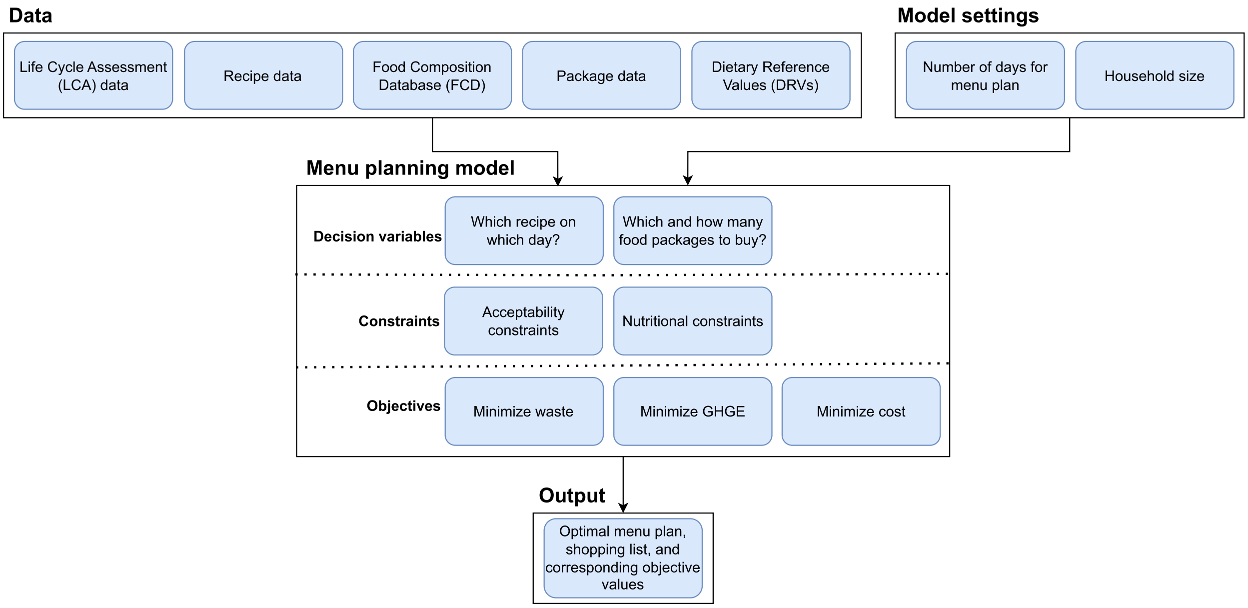

Fig. 1. General overview meal planning model and data.

recently, diet modeling has also been applied to find environmentally friendly diets. The review of van Dooren (2018) describes 12 diet modeling studies that incorporate environmental constraints. To the best of our knowledge, diet modeling has not yet been applied with the aim to reduce food waste, even though mathematical programming has been identified as an impactful way to research the trade-offs involved in the reduction of food waste (Akkaş and Gaur, 2022). Moreover, discrete package sizes have not been incorporated in dietary meal planning models before.

Translating the results of a diet model into practice is challenging. A diet model usually returns a list of quantities of food items, but does not guarantee that these items lead to feasible meals (Macdiarmid et al., 2012). For instance, breakfast cereals might be suggested without milk. Therefore, it is important to consider realistic combinations of ingredients when optimizing food planning to reduce household food waste. Benvenuti and De Santis (2020) argue that the acceptability of meal plans can be improved by considering culturally accepted recipes instead of ingredients and by considering the sequence of these recipes over time. In this article we therefore consider recipes and their sequence in a meal plan. We will refer to diet models that consider recipes for a complete meal as meal planning models.

Our research aims to develop a meal planning model that accounts for food waste using discrete package sizes. Food waste, greenhouse gas emissions, and costs are considered as objective functions in three different cases of single-objective optimization. In every optimization one objective is minimized while the values of the other two objectives are observed. We take the Netherlands as a case study. The remainder of this paper is structured as follows. In Section 2 the developed meal planning model is described, as well as the data that are used as input (for the model). The optimal meal plans and objective values are presented in Section 3 and discussed in Section 4. Finally, conclusions are drawn in Section 5.

2. Material and methods

Mixed-integer programming was used to estimate the extent to which household food waste could be reduced by better food planning. We designed a model that selects recipes from a database and formulates a dinner meal plan and shopping list (Fig. 1). The next subsections elaborate on the data sources used and model formulation.

2.1. Modeling approach

Mathematical modeling of diets can be defined as the use of mathematical techniques to formulate and optimize diets (Buttriss et al., 2014). A diet optimization model aims to find a combination of foods that best fulfills specific objectives while adhering to constraints, such as nutritional requirements or limits on food quantities. Diet modeling has been widely adopted for formulating nutritionally adequate, low cost, environmentally friendly diets, or for developing food-based dietary guidelines. We refer to van Dooren (2018) and Gazan et al. (2018) for an overview of diet modeling research.

In traditional diet modeling the quantities of ingredients in optimal diets are denoted by continuous decision variables. However, implementing the outcomes of these models may be challenging in practice, because the separate ingredients might not always combine into feasible meals (Macdiarmid et al., 2012). An alternative approach is dietary meal planning, where the decision variables refer to meals rather than individual ingredients. For example, Benvenuti et al. (2016) developed a meal planning model to formulate meal plans for Italian schools to reduce GHGE and water use.

To the best of our knowledge, we are the first to use dietary meal planning to reduce household food waste. Current dietary meal planning models do not consider retail package sizes, making it difficult to align purchases with the suggested food quantities in meal plans. Therefore, we developed a meal planning model in which we incorporated discrete package sizes.

We focused on modeling only dinners because foods usually consumed during dinner, such as potatoes, vegetables, and meats, have a considerable impact on food waste and the carbon footprint of the diet (Voedingscentrum, 2020). Furthermore, dinner foods are typically not consumed throughout the rest of the day in the Netherlands (RIVM, 2022). Also, individuals are less likely to vary their breakfast and lunch than their dinner.

It is assumed that all ingredients are purchased on the first day of the meal plan. All perishable ingredients that are left-over at the end of the meal plan (i.e. five days) are considered waste. Ingredients with a shelf-life of over one month are considered as shelf-stable, while the other ingredients are considered perishable. Furthermore, it is assumed that there are no left-overs after meal preparation, implying that all food in the meal plan is consumed.

The model has been solved using the Gurobi package in Python 3.6. The full mathematical model formulation is described in Appendix A. A textual explanation of the model is given in this section.

2.1.1. Decision variables

The model contains two main sets of decision variables. Firstly, binary variables indicate whether a recipe is planned for a given day. Secondly, integer variables represent the quantity of specific packages needed for each ingredient. Note that the model also contains sets of continuous decision variables. We refer to Appendix A.2 for a complete list of decision variables.

2.1.2. Objectives

Three objective functions are considered. In order to obtain outcomes on each of the three objective functions we treat each objective function individually as if we optimize only that objective ('single-objective optimization'). We minimize only that single objective while we observe what happens to the values of the other two objective functions. The objectives are as follows:

1. Total waste (grams). Defined as the total weight of left-over ingredients at the end of the meal plan.
2. Total CO_2 equivalent emission (grams). Defined as the CO_2 emission equivalent of the meal plan.
3. Total costs (€). Defined as the ingredient costs of the meal plan.

For perishable ingredients the impact of all packages purchased is considered, whereas for shelf-stable ingredients only the impact of the number of used grams is considered. For instance, if 3 grams of olive oil are required for a recipe, the cost of 3 grams is considered rather than the price for the entire bottle.

2.1.3. Constraints

Constraints are set up to ensure that exactly one recipe is selected on each day. Nutritional constraints ensure that water soluble nutrients intakes meet the requirements on a daily basis, whereas fat soluble nutrients, such as vitamin A, meet the requirements in the time span of the meal plan. The nutrient intakes may deviate 10% over the time span of the meal plan to allow for flexibility. Finally, constraints are set up to allow each ingredient planned on a day to deviate 10 grams from the recipe. This makes the model more realistic and flexible. For example, if you would have a zucchini that weighs 260 grams and the recipe prescribes 250 grams, you probably would use everything. We thus added a weight variation limit, which had to be imposed on all ingredients. It has been decided to limit the allowed variation to 10 grams, because for some ingredients, such as oil, a larger variation may have a considerate effect on the nutritional value of the meal.

2.2. Data

The Netherlands Nutrition Centre was used as the main source for the recipes in our model. The Netherlands Nutrition Centre is an institute funded by the Dutch government to provide independent information for healthy, safe, and sustainable food choices (Voedingscentrum, 2023). To create unity, ingredients in the Nutrition Centre recipes have been standardized to NEVO codes. These codes are used by the Dutch National Institute for Public Health and the Environment (RIVM) to refer to specific ingredients. The quantities mentioned in the recipes were standardized from other types of measurements, such as from tablespoon to grams, by using the database of the RIVM on Dutch portion sizes (RIVM, 2020). Furthermore, as this study focused on reducing edible food waste the food quantities were converted to edible weights (RIVM, 2020). An example of such an edible weight is the weight of a banana without the peel. The final recipe database used in this study consisted of 263 dinner recipes.

Package data have been obtained from a large Dutch retailer. For each food item, the net weight, package size in grams and package price was collected on January 18, 2023.

Life Cycle Assessment (LCA) was used to quantify the environmental impact of the meals planned. LCA is the most common methodological tool to assess the environmental impact of diets (Eme et al., 2019). In this research, LCAs from the RIVM were used (RIVM, 2021a). These LCAs describe each food's yearly average environmental impact from cradle to consumption, assuming it is purchased at a Dutch supermarket. This therefore accounts for seasonal differences in supply as, for instance, in winter tomatoes are imported from Spain whereas during summer Dutch tomatoes are sold in retail.

The Dutch Food Composition Database (FCD) was retrieved from the RIVM (RIVM, 2021b). The FCD contains the nutrient contents of the most common Dutch foods.

Dietary Reference Values (DRVs) are commonly accepted guidelines for different population groups to maintain their health through proper nutrition. These values were obtained from the Dutch Health Council (Gezondheidsraad, 2018, 2022). According to Statistics Netherlands (CBS) the most common household in the Netherlands consists of a man, a woman, and two children (CBS, 2023). This common household with a moderately active lifestyle is taken as a focal point of study. The intakes of the following micronutrients are constrained based on their public health importance in the Netherlands: vitamin A, vitamin B1, vitamin B2, folate equivalents, vitamin B12, vitamin C, calcium, iron, zinc, and saturated fats (RIVM, 2022). The DRVs used for dinner are shown in Appendix B.

3. Results

Minimizing waste (in grams) generated meal plans with no waste at all. The recipes selected and the corresponding shopping list of the meal plan with minimum waste are shown in Table 1. As one may expect, packages that are bought but not fully used for one recipe are used for another recipe on another day, thus limiting waste.

Table 1
Minimum waste meal plan and shopping list.

Menu plan: minimize waste	
Day 1	Ravioli with Mushrooms and Nuts
Day 2	Spinach Oven Dish
Day 3	Endive Mash with Mushrooms and Tofu-Nut Crumble
Day 4	Bulgur with Vegetables, Tofu, and Nuts
Day 5	Wheat with Tomatoes, Nuts, and Herbs

Shopping list: minimize waste			
ingredient	pack size (gr)	pack cost (€/kg)	buy
Tomato cherry raw	250	4.36	4
Spinach raw	400	4.98	3
Radish raw	100	9.90	2
Tahoe soya curd	200	10.45	2
Potatoes raw	1000	1.79	2
Veg stir-frying oriental	400	6.11	2
Milk semi-skimmed	500	1.90	1
Spinach raw	100	13.90	1
Tahoe soya curd	375	3.97	1
Spinach raw	200	8.95	1
Endive raw	500	5.38	1
Endive raw	1000	2.99	1
Mushroom raw	400	4.98	1

It is interesting to note that in the meal plan with minimum waste relatively expensive package sizes are chosen. For instance, 1500 grams of spinach are required for this meal plan (Table 1). The spinach is purchased as three packages of 400 grams (4.98 €/kg), one package of 200 grams (8.95 €/kg), and one package of 100 grams (13.90 €/kg)

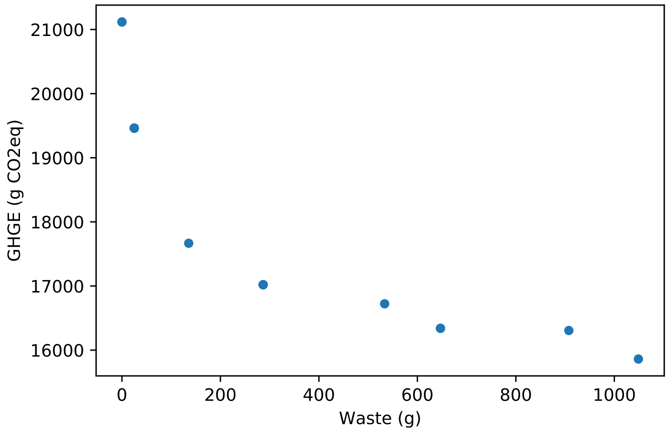

Fig. 2. Trade-off GHGE and waste (total for 4 persons for 5 days).

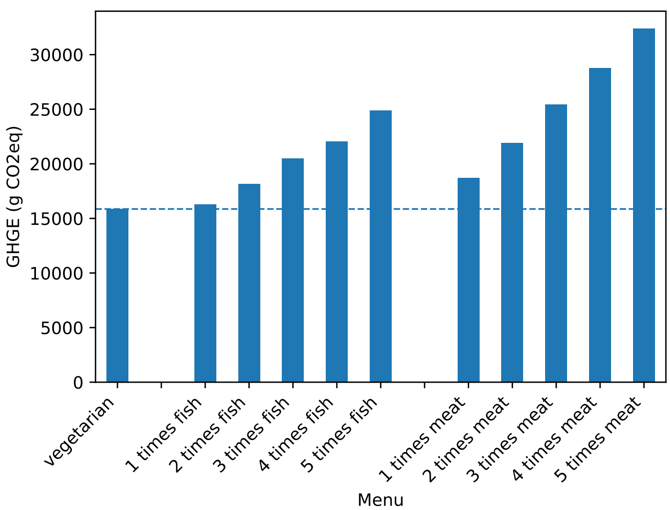

Fig. 3. Increases in GHGE of meal plans including fish and meat compared to the vegetarian meal plan (when minimizing GHGE, total for 4 persons for 5 days).

are selected. It would have been cheaper to purchase four packages of 400 grams, even though this is more than required in the recipe.

The model was also run with GHGE and cost as objective functions. The payoff table shows that the choice of objective function has a substantial impact on the results (Table 2). For instance, the cheapest meal plan (€1.66) has a relatively high carbon footprint (1237 gram CO_2), and waste (51 grams). The meal plan in which waste is minimized (0 grams) does not have the lowest carbon footprint (1056 grams CO_2). This finding might seem counter intuitive, hence an example. We compare two meal plans: meal plan A has components with a low carbon footprint and meal plan B has components with a high carbon footprint. Not wasting anything of meal plan B does not necessarily result in a diet with a lower carbon footprint than meal plan A, because meal plan A has a lower carbon footprint to begin with. This result is particularly intriguing because often an important underlying goal of minimizing food waste is to reduce the carbon footprint of the menu. We show that reducing waste does not necessarily coincide with reducing carbon footprint.

Fig. 2 shows a trade-off analysis for the carbon footprint and waste in grams of meal plans. As the carbon footprint and waste in grams are conflicting objectives (see Table 2), this is a so-called Pareto optimal set. In such a set the value of one objective cannot be improved without worsening the other objective. This requires a trade-off analysis between the objectives, which is conducted by applying the ϵ-constraint method. This is a method commonly used to address multi-objective programming problems (Miettinen, 1999). Specifically, a sequence of single-objective optimization problems is solved in which GHGE are minimized while imposing various upper bound levels of allowed food waste. Note that whereas in Table 2 values are portrayed per person per day, in Fig. 3 values are portrayed for four persons for five days. Each point on the graph represents a meal plan for four persons for five days. The recipes selected and the corresponding shopping list of the meal plan with minimum GHGE and cost are shown in Appendix C. Remarkably, the total weight of perishable ingredients on the minimum GHGE shopping list (13 kg) is higher than the weight of ingredients on the minimum waste shopping list (9 kg). Apparently, the minimum waste menu plan opts for ingredients with a higher dry matter content. This is worth noticing because purchasing more food in grams obviously implies that more food in grams could be wasted.

Table 2
Payoff table objective function and objectives (expressed per person per day, optimized for 4 persons for 5 days).

Objective	total waste (grams)	total GHGE (grams CO_2eq)	total cost (€)
Waste	0	1056	2.61
GHGE	52	793	3.07
Cost	43	1149	1.77

Table 3
Increases in objective values after excluding previously selected recipes from the dataset (total for 4 persons for 5 days).

Objective	0 recipes removed	5 recipes removed	10 recipes removed
Waste (g)	0	15.1	30.0
GHGE (g CO_2eq)	15861	19352	20005
Cost (€)	33.11	36.01	36.41

It is important to note that all recipes selected in the optimal meal plans in Fig. 2 and Table 2 are vegetarian. However, most people in the Netherlands eat meat and fish regularly (Dagevos and Verbeke, 2022). To assess the effect of flexitarian meals on the carbon footprint, meal plans are formulated in which GHGE are minimized and fish and meat had to be included (Fig. 3). Waste levels are not reported because they were considerately impacted by the limited recipe database. There are not enough recipes containing specific types of fish and meat, making it hard to combine them for a specific number of times per week to reduce food waste. Including recipes with fish into the meal plans raised GHGE; 3% for eating fish once a week, 14% for fish twice a week, and 29% for three times a week. Including recipes with meat into the meal plans also raised GHGE; 18% for once a week meat, 38% for twice a week, and 60% for three times a week. Even though the result that including meat and fish into diets increases GHGE is hardly surprising, this analysis draws a comparison with GHGE effects of reducing food waste. If the goal of reducing food waste is to simultaneously reduce GHGE, not only the level of waste should be considered but the carbon footprint of the diet as a whole.

To assess the sensitivity of the model's outcomes to the exclusion of recipes from the database, a sensitivity analysis has been conducted (Table 3). The model was run with the initial recipe database as input and waste, GHGE, and cost as objective functions. For each objective function, the recipes included in the meal plan were removed from the database and the model was run again. This was repeated once more. For instance, with the initial recipe database a meal plan with 0 grams of waste could be formulated. After removing the five recipes selected in this meal plan from the recipe database and running the model again, the minimum waste meal plan had 15.1 grams of waste. All objective values increased after removing recipes (Table 3). This result was to be expected, as removing recipes from the database decreases the solution space of the model. However, it is important to note that emphasis should therefore be placed on the relative rather than absolute differences between the objective values of the meal plans formulated in this study.

4. Discussion

The results described above demonstrate that meal planning using our optimization model reduces waste, while optimizing the use of discrete package sizes. The use of inappropriate package sizes is a significant cause of food waste (Williams et al., 2012; Chan, 2022). The results of this study show that it is possible to formulate meals without waste, taking into account available package sizes in the supermarket. Therefore, improved meal planning can be a way to omit waste caused by inappropriate package sizes.

The results also show that the cheapest meal plans have relatively high food waste and GHGE. This is caused by the model selecting large package sizes because of their relatively low prices. Apparently, for some products it is cheaper to buy large packages and waste a fraction than to buy a smaller more appropriate package. In general, consumers are inclined to purchase food in larger packages to take advantage of these quantity discounts (Petit et al., 2020). Therefore, pricing packages in proportion to sizes may help to reduce food waste, as also suggested by Wilson et al. (2017).

A trade-off analysis of the results shows that the meal plans with minimum waste have relatively high GHGE, and vice versa. As a result, we found that when focusing at minimizing GHGE the optimal result can lead to more waste in kilograms compared to when minimizing waste in kilograms as an objective. In current food waste research, food waste is foremost measured in kilograms. As the goal of reducing food waste is generally to reduce the environmental impact of the food system, we advocate to also consider GHGE as a performance indicator for food waste.

All of the meal plans suggested by the model consist of vegetarian recipes. Our analysis thus confirms that minimizing GHGE or costs implies eating vegetarian meals instead of meals with fish or meat. This is as expected, as the recipes in the database with fish and in particular meat generally have a higher carbon footprint and are more expensive than vegetarian alternatives.

Even though our study shows that, in theory, meal planning can generate meal plans without any food waste, it might be hard to stick to these meal plans in reality. For instance, a family member might spontaneously decide to eat elsewhere, or an extra person might join for dinner. Planning meals for only a part of the week instead of five days, and/or incorporating adjustable recipes, for instance by giving canned vegetables suggestions, might mitigate the effects of such disruptions. It is expected that meal kit services encounter the same challenges regarding flexibility. Furthermore, individual preferences for specific recipes have not been considered. Consumers may for example not like the taste of certain ingredients or prefer to vary carbohydrate sources throughout the week. Note that personal preferences regarding recipes and individual nutrient requirements can easily be implemented in the model by adding additional constraints.

The generalizability of this research is limited by the recipe database. Excluding recipes from the data set affects the results because the number of unique meal plans with good scores is relatively low (Table 3). Having more recipes in the database that conform to the nutritional guidelines increases the number of alternatives available and thus the solution space of the model, possibly leading to a larger variety of desirable results. For future research, an expansion of the database could allow for analyses comparing food waste in vegetarian, omnivorous, and pescetarian diets. Furthermore, assumptions regarding the physical dimensions of vegetables and fruits had to be made. In practice, consumers can sometimes choose whether to take slightly smaller or larger vegetables and fruits in the supermarket. Nonetheless, even with this limited data set the model can formulate meal plans with negligible waste.

5. Conclusions

This work aims to reduce household food waste by formulating meal plans using a dietary meal planning model, taking into account retail package sizes. To the best of our knowledge, this is the first study that considers retail package sizes in a dietary meal planning model. The results indicate that such a model can formulate meal plans that conform to the nutritional guidelines, have negligible food waste, low environmental impact, and low costs. These plans result in a focus on vegetarian meals during the week rather than meals containing fish or meat. Moreover, the results show that weight is not the best proxy for food waste if the goal of reducing food waste is to reduce environmental impact. We therefore advocate to explicitly consider greenhouse gas emissions of the whole diet when reporting food waste rather than only expressing food waste in kilograms.

While using a model to formulate meal plans shows that a reduction of food waste is possible, more research is needed on the extent to which meal plans will be adopted and followed in practice by households.

CRediT authorship contribution statement

M.A. van Rooijen: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **J.C. Gerdessen:** Writing – review & editing, Supervision, Methodology, Conceptualization. **G.D.H. Claassen:** Writing – review & editing, Supervision, Methodology, Conceptualization. **S.L.J.M. de Leeuw:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Meal planning model

The meal planning model aims to formulate a meal plan consisting of a dinner recipe per day for a household of X persons for Z days, while minimizing total greenhouse gas emissions, waste in grams, or total costs.

In this model the following assumptions are made:

- All ingredients are purchased on the first day of the recipe plan.
- It is assumed that exactly the amounts of food as described by the recipe plan are cooked. All perishable left-over ingredients are considered waste. E.g. if the plan prescribes to use 250 grams of minced meat and a package of 300 grams is selected, 50 grams are assumed to be waste.
- Ingredients with a shelf-life of over one month when opened are considered shelf-stable. Other ingredients are considered perishable.
- For shelf-stable ingredients, it is assumed that the packages with the lowest price per kg are used.

A.1. Sets and indices

$d \in \mathcal{D}$	Days
$i \in \mathcal{I}$	Ingredients
$j \in \mathcal{JD}$	Daily nutrients (water soluble)
$j \in \mathcal{JW}$	Weekly nutrients (fat soluble)
$p \in \mathcal{P}$	Package option (# of options vary per ingredient, each option has a package size and package price)
$r \in \mathcal{R}$	Recipes
$i \in \mathcal{S}$	Shelf-stable ingredients

A.2. Decision variables

$BUY_{i,p}$	Integer. Number of package options p to buy of ingredient i.
$Y_{r,d}$	Binary. Whether recipe r is planned on day d (1) or not (0).
$NIA_{j,d}$	Continuous. Nutrient intake of nutrient j on day d.
$P_{i,d}$	Binary. Whether ingredient i is planned on day d (1) or not (0).
PC_i	Continuous. Total purchase cost of all packages of ingredient i.
$REC_{i,d}$	Continuous. Grams of ingredient i needed on day d (according to the recipe).
$STOCK_{i,d}$	Continuous. Stock of ingredients i on day d after cooking.
$X_{i,d}$	Continuous. Grams of ingredient i planned on day d.

A.3. Parameters

$days$	Number of days for which to formulate a planning.
dev	Allowed deviation from DRVs.
drv_j	Dietary Reference Values (ADH and UL) for nutrient j.
$fcd_{i,j}$	Food Composition Database. Nutrient j in 100 grams of ingredient i.
lca_c_i	Carbon footprint in kg for ingredient i in kg.
lca_lu_i	Land use in m2a for ingredient i in kg.
$packs_{i,p}$	Packing size in grams per packing option p per ingredient i.
$packc_{i,p}$	Packing cost in euros per packing option p per ingredient i.
$pers$	Number of persons for whom to formulate a planning.
$rec_{i,r}$	Ingredient i in grams needed per person for recipe r.
$shelfs_i$	Binary. Whether an ingredient i is shelf-stable or not.

A.4. Objective function

Three objective terms are formulated. tot_ghge refers to the total CO_2 equivalent emission in grams of the recipe plan. This is computed by using LCA data of the ingredients. For perishable ingredients the CO_2 impact of all packages purchased is considered. For shelf-stable ingredients only the CO_2 impact of the number of grams actually used is considered. $waste\_grams$ refers to the number of grams of food wasted. In this model, everything that is left in the package of a perishable ingredient, e.g. not used in the planning, is assumed to be waste. tot_cost refers to the total cost of the recipe plan. For the shelf stable ingredients, only the cost of the number of grams used is computed. It is assumed that the largest and cheapest (per kg) package sizes are used for the shelf stable ingredients. For the perishable ingredients, also the proportion of the package that is not used, thus the part that is assumed to be wasted, is considered.

These objective terms are formulated mathematically as follows:

$$tot\_ghge = \sum_{i=1}^{I} lca\_c_i * STOCK_{i,0} \quad \forall i \notin \mathcal{S}$$
$$+ \sum_{i=1}^{I}\sum_{d=1}^{D} lca\_c_i * X_{i,d} \quad \forall i \in \mathcal{S}$$
$$waste\_grams = \sum_{i=1}^{I} STOCK_{i,d=max(\mathcal{D})} \quad \forall i \notin \mathcal{S}$$
$$tot\_cost = \sum_{d=1}^{D} packc_{i,p=max(\mathcal{P})}/max(\mathcal{P}) * X_{i,d} \quad \forall i \in \mathcal{S}$$
$$+ \sum_{p=1}^{|P_i|} packc_{i,p} * BUY_{i,p} \quad \forall i \notin \mathcal{S}$$

When one objective function is used, small fractions of the observed terms are used as tiebreakers to make sure that of the optimal alternatives, the alternative with the lowest value for the observed terms is selected. For example, the objective function could look like this:

$$Minimize\{tot\_ghge + tiebreaker\}$$

A.5. Constraints

The following constraints are formulated:

$$\sum_{r=1}^{R} Y_{r,d} = 1 \quad \forall d \in \mathcal{D} \quad (1.1)$$
$$\sum_{d=1}^{D} Y_{r,d} <= 1 \quad \forall r \in \mathcal{R} \quad (1.2)$$
$$REC_{i,d} = pers * \sum_{r=1}^{R} ingr_{i,r} * Y_{r,d} \quad \forall i \in \mathcal{I}, \forall d \in \mathcal{D} \quad (1.3)$$
$$REC_{i,d} >= 0.01 * P_{i,d} \quad \forall i \in \mathcal{I}, \forall d \in \mathcal{D} \quad (1.4)$$
$$X_{i,d} <= REC_{i,d} + 10 * P_{i,d} \quad \forall i \in \mathcal{I}, \forall d \in \mathcal{D} \quad (1.5)$$
$$X_{i,d} >= REC_{i,d} - 10 * P_{i,d} \quad \forall i \in \mathcal{I}, \forall d \in \mathcal{D} \quad (1.6)$$
$$STOCK_{i,0} = \sum_{p=1}^{|P_i|} packs_{i,p} * BUY_{i,p} \quad \forall i \in \mathcal{I} \quad (1.7)$$
$$STOCK_{i,d} = STOCK_{i,d-1} - X_{i,d} \quad \forall i \in \mathcal{I}, \forall d \in \mathcal{D} \quad (1.8)$$
$$NIA_{j,d} = \sum_{i=1}^{I} fcd_{i,j}/100 * X_{i,d} \quad \forall j \in \mathcal{J}, \forall d \in \mathcal{D} \quad (1.9)$$
$$NIA_{j,d} + NIAslack_{j,d} >= drvADH_j * pers * (1 - dev) \quad \forall j \in \mathcal{JD}, \forall d \in \mathcal{D} \quad (1.10)$$
$$NIA_{j,d} + NIAslack_{j,d} <= drvUL_j * pers * (1 + dev) \quad \forall j \in \mathcal{JD}, \forall d \in \mathcal{D} \quad (1.11)$$
$$\sum_{d=1}^{D} NIA_{j,d} + NIAslack_{j,d} >= drvADH_j * pers * (1 - dev) * days \quad \forall j \in \mathcal{JW} \quad (1.12)$$

$$\sum_{d=1}^{D} NIA_j + NIAslack_{j,d}$$

$$<= drvUL_j * pers * (1 + dev) * days \qquad \forall j \in \mathcal{JW} \qquad (1.13)$$

Constraints (1.1) make sure that one recipe r is planned per day. Constraints (1.2) make sure that the same recipe r cannot be planned twice within one planning. Constraints (1.3) compute how much of ingredient i is needed on day d according to the recipe. Constraints (1.4) make sure that binary variable $P_{i,d}$ is 1 if an ingredient i is planned on day d according to the recipe, 0 otherwise. Constraints (1.5) and constraints (1.6) allow the amount of ingredient i planned on day d to deviate 10 grams from the prescribed amount in the recipe used that day. Constraints (1.7) compute the total stock level in grams of ingredient i on the first day by summing the package types p bought of ingredient i. Constraints (1.8) compute the stock level of ingredient i for each day d after cooking. Constraints (1.9) compute the total nutrient contents of the meal plan. Constraints (1.10) and constraints (1.11) make sure that the total nutrient contents are higher than the ADH but lower than the UL of the dietary reference values for each water soluble nutrient j for each day d. Constraints (1.12) and constraints (1.13) make sure that the total intake of fat soluble nutrients j over the time span of the meal plan meets the dietary reference values. As fat soluble nutrients can be stored in the body, they do not have to be consumed in the same quantities every single day.

Appendix B. Dietary Reference Values (DRVs) for dinner

To determine the DRVs for only dinner, we assumed that nutrient intake remains unchanged throughout the rest of the day. The current average nutrient intakes and the average proportion of each nutrient consumed during dinner were used to compute current nutrient intakes throughout the rest of the day (RIVM, 2022). The unfulfilled portions of the Recommended Dietary Allowances (RDAs) of these nutrient intakes were set as the DRVs for dinner (Table B.1). For instance, the mean calcium intake of the case study household was 893.3 mg per person per day. Of this amount, 25.7% was consumed during dinner, which implies that 74.3% * 893.3 = 663.7 mg was consumed throughout the rest of the day. The RDA for calcium is 825 mg per day, which implies that 825 – 663.7 = 161.3 mg of calcium has to be consumed during dinner to meet the RDA. Recommended energy intakes were determined in the same way. It is important to note that this study did not aim to optimize dietary intake, and the DRVs merely acted as an estimation for a nutritionally adequate dinner.

Appendix C. Meal plan and shopping list minimum GHGE and minimum cost

Table C.1
Minimal GHGE meal plan and shopping list.

Menu plan: minimize GHGE	
Day 1	Mashed Endive with Almonds
Day 2	Lentil Burger with Spicy Carrot Salad
Day 3	Wheat with Tomatoes, Nuts, and Herbs
Day 4	Fennel-Radish Salad with Walnuts and Mashed Potatoes
Day 5	Stew with Parsnips and White Beans

Shopping list: minimize GHGE

ingredient	pack size (gr)	pack cost (€/kg)	buy
Parsnip raw	400	4.22	4
Tomato cherry raw	250	4.36	4
Fennel raw	250	4.20	3
Potatoes raw	1000	1.79	3
Radish raw	100	9.90	3
Beans white canned	360	3.19	2
Carrot raw av	500	2.18	2
Milk semi-skimmed	500	1.90	2
Carrot raw av	300	3.33	2
Endive raw	400	4.72	2
Lentils red boiled	150	14.33	2
Rocket raw	150	11.93	1
Endive raw	250	5.56	1
Leek raw	160	4.31	1
Chili pepper raw	10	45.00	1
Juice orange	330	1.36	1
Carrot raw av	650	4.60	1
Bread pita white	400	1.88	1

Table C.2
Minimal cost meal plan and shopping list.

Menu plan: minimize cost	
Day 1	Spicy Chinese Cabbage
Day 2	Spiced Couscous with Nuts
Day 3	Spinach Lasagna with Hazelnuts
Day 4	Pizza
Day 5	Pumpkin Risotto with Pearl Barley and Sage

Shopping list: minimize cost

ingredient	pack size (gr)	pack cost (€/kg)	buy
Cabbage Chinese raw	780	2.17	4
Tomatoes tinned	400	1.72	3
Spinach frozen boiled	450	1.44	2
Egg whole chicken av raw	348	7.44	1
Cheese 30+ av	175	21.66	1
Cheese Ricotta	100	14.9	1
Leek raw	160	4.31	1
Mushroom raw	250	5.96	1
Anchovy in oil canned	46	38.91	1
Cheese cottage	200	4.45	1

Table B.1
DRVs for dinner (shown in the last column) for an average family, based on the difference between the RDAs and current nutrient intakes apart from dinner. NI: nutrient intake.

	Current NI[a]	% NI dinner	NI except dinner[a]	RDA[a]	DRV dinner[a]
Energy (kcal)	8042.0	34%	5300.0	7588.0	2288.0
Total protein (g)	283.0	43%	162.7	160.0	-[b]
Saturated fatty acids (g)	111.0	36%	71.2	78.0	6.8[c]
Retinol activity eq (μg)	2677.0	38%	1670.4	2280.0	609.6
Vitamin B1 (mg)	4.0	42%	2.3	2.6	0.2
Vitamin B2 (mg)	5.4	32%	3.7	4.6	0.9
Folate equivalents (μg)	858.6	37%	540.9	900.0	359.1
Vitamin B12 (μg)	15.2	41%	9.0	8.2	-[b]
Vitamin C (mg)	348.4	46%	188.5	230.0	41.5
Calcium (mg)	3573.2	26%	2654.9	3300.0	645.1
Iron (mg)	36.0	35%	23.3	45.0	21.7
Zinc (mg)	36.2	42%	21.1	30.0	8.9

[a] For an average Dutch family of a man, a woman, and two children with a moderately active lifestyle.
[b] The NI throughout the rest of the day already fulfills the RDA, no constraint is required.
[c] The RDA for saturated fatty acids is an upper bound. This upper bound is not enforced because the NI throughout the rest of the day is too high. Even though the recipes used are relatively low in saturated fatty acids, it is impossible to meet the RDA.

References

Akkaş, A., Gaur, V., 2022. Om forum—reducing food waste: an operations management research agenda. Manuf. Serv. Oper. Manag. 24, 1261–1275.

Benvenuti, L., De Santis, A., 2020. Making a sustainable diet acceptable: an emerging programming model with applications to schools and nursing homes menus. Front. Nutr. 7, 562833.

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.

Chan, R.B.Y., 2022. A review of packaging-related studies in the context of household food waste: drivers, solutions and avenues for future research. Packag. Technol. Sci. 35, 3–51.

Boulet, M., Hoek, A.C., Raven, R., 2021. Towards a multi-level framework of household food waste and consumer behaviour: untangling spaghetti soup. Appetite 156, 104856.

Buttriss, J.L., Briend, A., Darmon, N., Ferguson, E.L., Maillot, M., Lluch, A., 2014. Diet modelling: how it can inform the development of dietary recommendations and public health policy. Nutr. Bul. 39 (1), 115–125.

Caldeira, C., Laurentiis, V.D., Corrado, S., van Holsteijn, F., Sala, S., 2019. Quantification of food waste per product group along the food supply chain in the European Union: a mass flow analysis. Resour. Conserv. Recycl. 149, 479–488.

CBS (2023). Statistics Netherlands: Huishoudens; grootte, samenstelling, positie in het huishouden, 1 januari [data file]. (Accessed 9 August 2023).

Dagevos, H., Verbeke, W., 2022. Meat consumption and flexitarianism in the low countries. Meat Sci. 192, 108894.

Eme, Paul Eze, Douwes, Jeroen, Kim, Nicholas, Foliaki, Sunia, Burlingame, Barbara, 2019. Review of methodologies for assessing sustainable diets and potential for development of harmonised indicators. Int. J. Environ. Res. Public Health 16 (7), 1184.

FAO, 2013. Food wastage footprint: Impacts on natural resources. Summary report.

Flycatcher, 2019. Voedselverspilling.

Gazan, R., Brouzes, C.M., Vieux, F., Maillot, M., Lluch, A., Darmon, N., 2018. Mathematical optimization to explore tomorrow's sustainable diets: a narrative review. Adv. Nutrition 9, 602–616.

Gezondheidsraad (2018). Voedingsnormen voor vitamines en mineralen voor volwassenen. publicatienr. 2018/19 [data file]. (Accessed 9 August 2023).

Gezondheidsraad (2022). Voedingsnormen voor energie. publicatienr. 2022/19 [data file]. (Accessed 9 August 2023).

Graham-Rowe, E., Jessop, D.C., Sparks, P., 2014. Identifying motivations and barriers to minimising household food waste. Resour. Conserv. Recycl. 84, 15–23.

Gustavsson, J., Cederberg, C., Sonesson, U., 2011. Global Food Losses and Food Waste. Food and Agriculture Organization of the United Nations.

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, 632–639.

Miettinen, K., 1999. Nonlinear Multiobjective Optimization, vol. 12. Springer Science & Business Media.

Petit, O., Lunardo, R., Rickard, B., 2020. Small is beautiful: the role of anticipated food waste in consumers' avoidance of large packages. J. Bus. Res. 113, 326–336.

RIVM (2020). Portie-online versie 2020/1.4 [data file]. (Accessed 9 August 2023).

RIVM (2021a). Milieubelasting van voedingsmiddelen [data file]. (Accessed 9 August 2023).

RIVM (2021b). Nevo-online version 2021/7.1 [data file]. (Accessed 9 August 2023).

RIVM (2022). Voedselconsumptiepeiling 2012-2016 (vcp 2012-2016) [data file]. 2022, March 5.

Romani, S., Grappi, S., Bagozzi, R.P., Barone, A.M., 2018. Domestic food practices: a study of food management behaviors and the role of food preparation planning in reducing waste. Appetite 121, 215–227.

Roodhuyzen, D.M., Luning, P.A., Fogliano, V., Steenbekkers, L.P., 2017. Putting together the puzzle of consumer food waste: towards an integral perspective. Trends Food Sci. Technol. 68, 37–50.

Schanes, K., Dobernig, K., Gözet, B., 2018. Food waste matters - a systematic review of household food waste practices and their policy implications. J. Clean. Prod. 182, 978–991.

Spang, E.S., Moreno, L.C., Pace, S.A., Achmon, Y., Donis-Gonzalez, I., Gosliner, W.A., Jablonski-Sheffield, M.P., Momin, M.A., Quested, T.E., Winans, K.S., Tomich, T.P., 2019. Food loss and waste: measurement, drivers, and solutions. Annu. Rev. Environ. Resour. 44, 117–156.

Stangherlin, I., de Barcellos, M., 2018. Drivers and barriers to food waste reduction. Br. Food J. 120, 2364–2387.

Stefan, V., van Herpen, E., Tudoran, A.A., Lähteenmäki, L., 2013. Avoiding food waste by Romanian consumers: the importance of planning and shopping routines. Food Qual. Prefer. 28 (1), 375–381.

Stenmarck, Â., Jensen, C., Quested, T., Moates, G., Buksti, M., Cseh, B., Juul, S., Parry, A., Politano, A., Redlingshofer, B., et al., 2016. Estimates of European Food Waste Levels. IVL Swedish Environmental Research Institute.

van Dooren, C., 2018. A review of the use of linear programming to optimize diets, nutritiously, economically and environmentally. Front. Nutr. 5, 48.

Voedingscentrum, 2020. Voedselverspilling door consumenten - factsheet. https://www.voedingscentrum.nl/Assets/Uploads/voedingscentrum/Documents/Professionals/Pers/Factsheets/Factsheet%20voedselverspilling.pdf. (Accessed 9 August 2023).

Voedingscentrum, 2023. The Netherlands Nutrition Centre. https://www.voedingscentrum.nl. (Accessed 9 August 2023).

Watson, M., Meah, A., 2012. Food, waste and safety: negotiating conflicting social anxieties into the practices of domestic provisioning. Sociol. Rev. 60, 102–120.

Williams, H., Wikström, F., Otterbring, T., Löfgren, M., Gustafsson, A., 2012. Reasons for household food waste with special attention to packaging. J. Clean. Prod. 24, 141–148.

Wilson, N.L., Rickard, B.J., Saputo, R., Ho, S.-T., 2017. Food waste: the role of date labels, package size, and product category. Food Qual. Prefer. 55, 35–44.