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Research Paper

# Hospital food management: a multi-objective approach to reduce waste and costs

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ABSTRACT

Food waste contributes significantly to greenhouse emissions and represents a substantial portion of overall waste within hospital facilities. Furthermore, uneaten food leads to a diminished nutritional intake for patients, that typically are vulnerable and ill. Therefore, this study developed mathematical models for constructing patient meals in a 1000-bed hospital located in Florida. The objective is to minimize food waste and meal-building costs while ensuring that the prepared meals meet the required nutrients and caloric content for patients. To accomplish these objectives, four mixed-integer programming models were employed, incorporating binary and continuous variables. The first model establishes a baseline for how the system currently works. This model generates the meals without minimizing waste or cost. The second model minimizes food waste, reducing waste up to 22.53 % compared to the baseline. The third model focuses on minimizing meal-building costs and achieves a substantial reduction of 37 %. Finally, a multi-objective optimization model was employed to simultaneously reduce both food waste and cost, resulting in reductions of 19.70 % in food waste and 32.66 % in meal-building costs. The results demonstrate the effectiveness of multi-objective optimization in reducing waste and costs within large-scale food service operations.

## 1. Introduction

Over the course of centuries, human endeavors have contributed to the evolution of global society and economy. However, this has had detrimental impacts on the environment. The healthcare system alone is estimated to cause 1–5% of total global environmental damage (Lenzen et al., 2020) and bears significant responsibility for the emission of air pollutants. It is the source of 12 % of acid rain, and 10 % of smog formation (Eckelman and Sherman, 2016). Furthermore, healthcare waste is infectious, potentially endangering human health (Coban et al., 2023). In the US, the healthcare system generates 8.4 kg of waste per bed daily (Minoglou et al., 2017).

The extent of food waste within hospital settings exceeds that of any other food service sector by a factor of 2–3 (Dias-Ferreira et al., 2015). Moreover, food waste accounts for slightly less than one-fourth of municipal solid waste (Synani et al., 2021), and in certain hospital settings, it represents the most substantial portion of the overall waste stream (Carino et al., 2020). In Vietnam, for instance, a study indicated that 25 % of the overall waste generated consists of food or originates from kitchen-related sources (Diaz et al., 2008).

Numerous stages of food processing, such as ingredient transportation, food preparation, and food left uneaten, significantly contribute to this issue. However, in this study, the term "food waste" refers to food served to patients that goes unconsumed, which constitutes a noteworthy proportion of approximately 30 % and can account for up to 65 % of all food served (Williams and Walton, 2011).

A study conducted at a 1000-bed hospital in the state of Georgia in the US demonstrated that on average 29 tons of food waste are generated annually (Alshqaqeeq et al., 2017). Comparable patterns have been observed in other countries. For instance, a study in Bangladesh revealed that food waste accounted for 74 % of all medical waste in a hospital (Hossain et al., 2014). Similarly, a study of three hospitals in Italy estimated that 41.6 % of food served to patients was discarded (Schiavone et al., 2019). In Portugal, another study revealed that hospitals across the country dispose of roughly 8.7 thousand tons of food waste annually (Dias-Ferreira et al., 2015). This indicates significant mismanagement of resources, given that food waste is predominantly disposed of in landfills (ElBilali and Ben Hassen, 2020) or sewerage

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systems (Mbongwe et al., 2008).

The exploration of medical food waste in the literature primarily revolves around the measurement and mitigation of food waste. Most studies adopted strategies where the amount of food waste was measured before and after a modification in the system. The applied modifications include patient autonomy in portion selection (Ofei et al., 2014), the provision of dining rooms (Williams and Walton, 2011), the adoption of texture-modified diets (Razalli et al., 2021), and the development of room service delivery (McCray et al., 2018; Kuperberg et al., 2008).

The implementation of room service in a public adult facility in Australia resulted in a decrease of 13 % in the overall average food waste (McCray et al., 2018). The study concluded that this strategy led to cost savings in patient food expenditures, while enhancing energy and protein intake, and improving patient satisfaction levels.

The same initiative was implemented in a pediatric hospital in Canada (Kuperberg et al., 2008). As a result, cost reductions of 36 % at breakfast, 29 % at lunch, and 19 % at dinner, and a 23 % reduction in food waste were generated. The caloric intake was also reduced, and patients' satisfaction increased.

In Strotmann et al. (2017), the researchers aimed to reduce food waste at three locations: a hospital, the hospital cafeteria, and a residential home. The involvement of employees was integral to the formulation and execution of measures aimed at waste reduction, which include raising awareness among employees regarding food waste, establishing continuous feedback mechanisms throughout the supply chain, and adjusting portion sizes based on target-specific standards and requirements. The implementation of these strategies yielded a substantial decrease in average waste rates: a reduction from 21.4 % to 13.4 % in the residential home and from 19.8 % to 12.8 % in the cafeteria.

A study carried out in Wales indicated that patients were asked about their preference for consuming a hot meal, yet this information was not utilized to adjust the quantity of food prepared, leading to an overestimation of the required meal count (Sonnino and McWilliam, 2011). Additional insights derived from this study indicate that insufficient staffing capabilities hindered the accommodation of patient choices. Furthermore, inadequate descriptions of the menu, deficiencies in infrastructure, and the overall substandard quality of the hospital meal service were factors contributing to the generation of food waste.

Other investigations have explored the establishment of a circular economy through the practice of composting food waste, an environmentally mindful approach to waste diversion (Amodeo and Klimas, 2021). This approach facilitates the restoration of nutrients to the soil, facilitating subsequent food production. In developed countries, several commonly employed methods for managing waste, including infectious healthcare waste, are: autoclaving, microwave chemical disinfection, incineration, and ground disposal (Diaz et al., 2005). Additionally, Torkayesh et al. (2021) suggest using stratified multi-criteria decision-making methods (MCDM) for waste disposal, which considers uncertainty.

Within the realm where medical waste and optimization intersect, Michlowicz (2012) presents a model that aims to optimize the transport and production process pertaining to medical waste. Furthermore, other studies have examined the association between the generation of food waste and several patient-related factors, including the dietary patterns of patients (Gomes et al., 2020).

### 1.1. Contributions

When reviewing the existing literature, the significant gap in addressing the issue of food waste management becomes evident, particularly in the context of meal planning for patients. While many studies have quantified the extent of waste generated, they frequently fail to consider the cost and to propose methods to manage or mitigate the food waste. On the other hand, articles suggesting how to minimize waste were mostly practice-based and lacked mathematical frameworks that could provide a comprehensive analysis.

Furthermore, the limited research on this topic containing mathematical models addressed the transport and production process, leaving a substantial void in optimizing meal planning. This highlights the need for optimization models supporting the design of meals for patients, guaranteeing the fulfillment of the nutritional and caloric requirements, and reducing food waste and meal-building costs.

This paper aims to address the aforementioned gap by presenting a comprehensive and solution-oriented framework to optimize patient meal planning. Concretely, the study aims to:

1. Develop mathematical models to minimize food waste and meal-building costs, enhancing overall system efficiency and reducing adverse environmental impacts. Single-objective and multi-objective models will help quantify the extent of improvement achievable.
2. Provide weekly meal plans tailored to patients' specific nutritional and caloric requirements and customized to their age, gender, ward, and dietary needs.
3. Validate the applicability of the models with real-world data, ensuring that the developed framework can be replicated across various hospital settings, accommodating different patient demands and dietary needs.

The obtained insights shed light on the unsolved issue of food waste generation in the healthcare system. Furthermore, this paper presents the first model designed to minimize food waste and meal-building costs in healthcare facilities. Ultimately, this study directs and expands the efforts of the operations research and management science societies within the healthcare sector.

## 2. Methods

This study applies mixed-integer programming (MIP) models for single and multi-objective optimization, with the food waste and the cost of building the meals of the patients being the two objectives to minimize.

### 2.1. Model description

The model generates a weekly meal plan for all patients admitted to the hospital, categorizing them by age range, gender, diet, and ward. Let $\Delta, \Omega, D,$ and $P$ denote the sets of days of the week, wards, diets, and patient profiles, respectively. The notations $\delta \in \Delta, \omega \in \Omega, \sigma \in D,$ and $\rho \in P$ will represent specific instances from these sets.

Furthermore, the model incorporates a scenario where patients have food intolerance. Let $V$ be the set of food intolerance scenarios, where each scenario $\alpha$ is an element of $V$. The set has two elements: $\alpha = 0$ and $\alpha = 1$. The scenario where patients have food intolerance is $\alpha = 1$, and in this case, the composition of the meals is adjusted to avoid food items that could potentially cause intolerance. Conversely, $\alpha = 0$ denotes the scenario where the patients do not have food intolerance, and therefore there is no restriction of food items. Let $I$ be the set of eligible food items that can be included in a patient's meal, where each food item $i$ is an element of $I$. The binary parameter $a_i$ indicates whether the food item $i \in I$ causes intolerance. In the case of patients with food intolerance, these food items are excluded from their meals. The demand for each category of patient is denoted as $q_{\rho\omega}^{\sigma\alpha\delta}$.

The meals were designed to fulfill the nutrient and caloric requirements of each category of patient according to age range, gender, diet, and ward. Let $U$ be the set of food nutrients to be considered, where each food nutrient $\mu$ is an element of $U$, and $S$ be the set of food groups, where each food group $\tau$ is an element of $S$. Each patient requires $r_{\mu\rho}$ grams of nutrient $\mu \in U$, a caloric intake ranging from $b_\rho$ to $t_\rho$ calories, and a minimum percentage $e_{\rho\tau}$ of the food group $\tau \in S$ present in their meal. The binary parameter $g_{i\tau}$ indicates whether the food item $i \in I$

belongs to the food group $\tau \in S$.

Each unit of food item $i \in I$ has a cost of $c_i$ dollars, contains $p_i$ calories, and has $n_{i\rho}$ grams of food nutrient $\mu \in U$. The waste percentage of food item $i \in I$ per patient with profile $\rho \in P$ on ward $\omega \in \Omega$ is denoted as $w_{i\omega\rho}$.

The model contains continuous and binary variables. The continuous variable $x_{i\omega\alpha}^{\rho\sigma\delta}$ represents the amount of food item $i \in I$ that should be served to a patient from ward $\omega \in \Omega$, considering food intolerance scenario $\alpha \in V$, profile $\rho \in P$, diet $\sigma \in D$, on day $\delta \in \Delta$. The binary variable $y_{i\omega\alpha}^{\rho\sigma\delta}$ takes the value of 1 if the food item $i$ is served to the patient and 0 otherwise.

Some of the constraints of the model are applied to specific instances of each set. For that purpose, let $\sigma'$ represent the low-sodium diet, $\sigma''$ represent the vegetarian diet, $\mu'$ represent sodium in the food nutrients, and $\tau'$ represent the food group protein. Moreover, some constraints were applied to subsets of each set. Consequently, let $I'$ represent the subset of food items containing meat, $D'$ represent the subset of regular and low-sodium diets, and $\Delta'$ represent the subset of consecutive days that each meal should not be repeated for a patient. To assist the reader, the sets, parameters, and variables of the model are given in the Appendix.

### 2.2. Mathematical formulation

The optimization models applied in this study aim to build the optimal meal that satisfies the caloric and nutritional requirements of distinct populations. The optimality of the meal is contingent upon the objective function selected, which may involve minimizing food waste, reducing the costs associated with meal construction, or a combination of both factors.

#### 2.2.1. Objectives

*2.2.1.1. Minimizing food waste.* The objective function (1) aims to minimize the summation of food items $i \in I$ to be served to patients in ward $\omega \in \Omega$, considering food intolerance scenario $\alpha \in V$, with profile $\rho \in P$, following diet $\sigma \in D$, on day $\delta \in \Delta$ of the week, multiplied by the number of patients $q_{\rho\omega}^{\sigma\alpha\delta}$ and by the percentage of food item $i$ wasted per patient denoted by $w_{i\omega\rho}$. The summation is performed for all combinations of food items, wards, food intolerance scenarios, patient profiles, diets, and days of the week. This represents the total food waste.

$$\text{Min} \sum_{i \in I} \sum_{\omega \in \Omega} \sum_{\alpha \in V} \sum_{\rho \in P} \sum_{\sigma \in D} \sum_{\delta \in \Delta} x_{i\omega\alpha}^{\rho\sigma\delta} q_{\rho\omega}^{\sigma\alpha\delta} w_{i\omega\rho} \tag{1}$$

*2.2.1.2. Minimizing the meal-building costs.* Objective function (2) aims to minimize the summation of food items $i \in I$ to be served to patients on ward $\omega \in \Omega$, considering food intolerance scenario $\alpha \in V$, with profile $\rho \in P$, following diet $\sigma \in D$, on day $\delta \in \Delta$ of the week, multiplied by the quantity of patients $q_{\rho\omega}^{\sigma\alpha\delta}$ and by $c_i$, the cost of food item $i \in I$. The summation is performed for all combinations to capture the overall meal-building costs.

$$\text{Min} \sum_{i \in I} \sum_{\omega \in \Omega} \sum_{\alpha \in V} \sum_{\rho \in P} \sum_{\sigma \in D} \sum_{\delta \in \Delta} x_{i\omega\alpha}^{\rho\sigma\delta} q_{\rho\omega}^{\sigma\alpha\delta} c_i \tag{2}$$

#### 2.2.2. Constraints

This section introduces the constraints of the MIP formulation.

Equation (3) guarantees that the food served contains the essential nutrients required by each patient per meal. This condition holds for every food nutrient $\mu \in U$ for all patients. The calculation of the received nutrients involves the multiplication of the units of food received by their corresponding nutrient values.

$$\sum_{i \in I} x_{i\omega\alpha}^{\rho\sigma\delta} n_{i\mu} \geq r_{\mu\rho} \ \forall \mu \in U, \omega \in \Omega, \alpha \in V, \rho \in P, \sigma \in D, \delta \in \Delta \tag{3}$$

Equations (4) and (5) ensure that the caloric content of each meal remains within the prescribed range for all patient categories, avoiding deficiencies and excesses.

Equation (4) states that the product of the quantity of food served in the meal $x_{i\omega\alpha}^{\rho\sigma\delta}$ and the caloric content $p_i$ of such quantity must be equal to or exceed the minimum caloric requirements $b_\rho$ for each category of patient.

$$\sum_{i \in I} x_{i\omega\alpha}^{\rho\sigma\delta} p_i \geq b_\rho \ \forall \omega \in \Omega, \alpha \in V, \rho \in P, \sigma \in D, \delta \in \Delta \tag{4}$$

Constraint (5) states that the product of the quantity of food served in the meal $x_{i\omega\alpha}^{\rho\sigma\delta}$ and the caloric content $p_i$ of such quantity must be equal to or less than the maximum caloric requirements $t_\rho$ for each category of patient.

$$\sum_{i \in I} x_{i\omega\alpha}^{\rho\sigma\delta} p_i \leq t_\rho \ \forall \omega \in \Omega, \alpha \in V, \rho \in P, \sigma \in D, \delta \in \Delta \tag{5}$$

In equation (6), for each food group $\tau \in S$, ward $\omega \in \Omega$, patient profile $\rho \in P$, diet $\sigma \in D$, and day $\delta \in \Delta$, the summation of the amount of all food items $i \in I$ multiplied by the binary parameter $g_{i\tau}$ determines the total quantity of food in that particular food group for the given patient category. This outcome should be greater than or equal to the minimum required for the given patient category, which is determined by the summation of the amount of all food items $i \in I$ multiplied by the minimum proportion associated with the respective food group, represented by $e_{\rho\tau}$. Therefore, the amount of food in the meal meets the minimum required amount of each food group for all patient categories.

$$\sum_{i \in I} x_{i\omega\alpha}^{\rho\sigma\delta} g_{i\tau} \geq \sum_{i \in I} x_{i\omega\alpha}^{\rho\sigma\delta} e_{\rho\tau} \ \forall \omega \in \Omega, \alpha \in V, \rho \in P, \sigma \in D, \delta \in \Delta, \tau \in S \tag{6}$$

Constraint (7) states that the sum of the multiplication of the quantity of food item $i \in I$ served to patients adhering to the low-sodium diet $x_{i\omega\alpha}^{\rho\sigma'\delta}$ and the sodium content present in that particular quantity of food $n_{i\mu'}$ must be equal to or less than the maximum permissible sodium intake for patients following such diet so they will not surpass the prescribed sodium limit.

$$\sum_{i \in I} x_{i\omega\alpha}^{\rho\sigma'\delta} n_{i\mu'} \leq F \ \forall \omega \in \Omega, \alpha \in V, \rho \in P, \delta \in \Delta \tag{7}$$

In constraint (7), $\sigma'$ represents the low-sodium diet, $\mu'$ represents sodium in the food nutrients, and $F$ is the maximum amount of sodium that can be ingested during one meal by patients following the low-sodium diet.

Equation (8) is implemented among individuals following the vegetarian diet and assures there is zero animal meat present in their meals.

$$x_{i\omega\alpha}^{\rho\sigma''\delta} = 0 \ \forall i \in I', \omega \in \Omega, \alpha \in V, \rho \in P, \delta \in \Delta \tag{8}$$

In equation (8), $\sigma''$ represents the vegetarian diet and $I'$ represents the food items containing meat.

Constraint (9) guarantees that the meals of patients with food intolerance do not include food items with the potential to trigger the intolerance.

$$x_{i\omega 1}^{\rho\sigma\delta} a_i = 0 \ \forall i \in I, \omega \in \Omega, \rho \in P, \sigma \in D, \delta \in \Delta \tag{9}$$

In constraint (9), $a_i$ is a binary parameter indicating whether the food item is likely to cause food intolerance.

Expression (10) ensures that each meal will contain one type of protein. In this equation, $\tau'$ represents the food group protein.

$$\sum_{i\in I} y_{i\omega\alpha}^{\rho\sigma\delta} g_{i\tau'} \leq 1 \; \forall \; \omega \in \Omega, \; \alpha \in V, \rho \in P, \sigma \in D, \delta \in \Delta \quad (10)$$

Constraint (11) ensures that consecutive meals provided to patients at the facility are not identical. This constraint promotes dietary diversity in terms of protein composition across the designated days for most diets. The binary variable $y_{i\omega\alpha}^{\rho\sigma\delta}$ indicates if the food item $i \in I$ was included in the meal of a specific patient category. Additionally, the binary parameter $g_{i\tau'}$ denotes whether the food item $i \in I$ belongs to the food group $\tau \in S$. To limit the presence of each protein to one of the selected days, the summation over the days is restricted to less than or equal to 1.

$$\sum_{\delta\in\Delta'} y_{i\omega\alpha}^{\rho\sigma\delta} g_{i\tau'} \leq 1 \; \forall \; i \in I, \omega \in \Omega, \; \alpha \in V, \rho \in P, \sigma \in D' \quad (11)$$

In equation (11), $\Delta'$ represents the consecutive days that the meal should not be repeated, $\tau'$ represents the food group protein, and $D'$ the set of diets for which this constraint will be applicable.

Furthermore, there is interdependency among the variables $x_{i\omega\alpha}^{\rho\sigma\delta}$ and $y_{i\omega\alpha}^{\rho\sigma\delta}$ because $y_{i\omega\alpha}^{\rho\sigma\delta}$ assumes the value 1 when $x_{i\omega\alpha}^{\rho\sigma\delta}$ is greater than 0, and conversely, $y_{i\omega\alpha}^{\rho\sigma\delta}$ is 0 when $x_{i\omega\alpha}^{\rho\sigma\delta}$ is 0. For this relationship to be applicable, the following constraints are needed:

The variable $y_{i\omega\alpha}^{\rho\sigma\delta}$ will take the value 1 if the variable $x_{i\omega\alpha}^{\rho\sigma\delta}$ is positive, as indicated by constraint (12). This condition can be enforced by using the big M technique. When $x_{i\omega\alpha}^{\rho\sigma\delta}$ is positive, the product of $y_{i\omega\alpha}^{\rho\sigma\delta}$ and $M$ must exceed the value of $x_{i\omega\alpha}^{\rho\sigma\delta}$. Given that $y_{i\omega\alpha}^{\rho\sigma\delta}$ is a binary variable, this condition is only satisfied when $y_{i\omega\alpha}^{\rho\sigma\delta}$ assumes the value 1.

$$x_{i\omega\alpha}^{\rho\sigma\delta} \leq y_{i\omega\alpha}^{\rho\sigma\delta} M \; \forall \; i \in I, \omega \in \Omega, \; \alpha \in V, \rho \in P, \sigma \in D, \delta \in \Delta \quad (12)$$

Constraint (13) uses the small m technique to guarantee the assignment of the value 0 to variable $y_{i\omega\alpha}^{\rho\sigma\delta}$ if $x_{i\omega\alpha}^{\rho\sigma\delta}$ equals 0. To satisfy this condition, the product of the value of $y_{i\omega\alpha}^{\rho\sigma\delta}$ and $m$ must be less than or equal to $x_{i\omega\alpha}^{\rho\sigma\delta}$. Consequently, when $x_{i\omega\alpha}^{\rho\sigma\delta}$ is 0, the value of $y_{i\omega\alpha}^{\rho\sigma\delta}$ will be 0.

$$y_{i\omega\alpha}^{\rho\sigma\delta} m \leq x_{i\omega\alpha}^{\rho\sigma\delta} \; \forall \; i \in I, \omega \in \Omega, \; \alpha \in V, \rho \in P, \sigma \in D, \delta \in \Delta \quad (13)$$

Finally, the domain of the variables is expressed in the constraints (14) and (15):

$$x_{i\omega\alpha}^{\rho\sigma\delta} \in \mathbb{R}^{+} \; \forall \; i \in I, \omega \in \Omega, \; \alpha \in V, \rho \in P, \sigma \in D, \delta \in \Delta \quad (14)$$

$$y_{i\omega\alpha}^{\rho\sigma\delta} \in [0, 1] \; \forall \; i \in I, \omega \in \Omega, \; \alpha \in V, \rho \in P, \sigma \in D, \delta \in \Delta \quad (15)$$

#### 2.2.3. Settings

The model was executed under four configurations, all of which satisfy the nutritional requirements for each type of patient. The first is a feasibility problem that aims to construct the meals without minimizing food waste or cost. In this setting, the solver minimizes a constant that does not force the variables' values in any specific direction. The result is a feasible solution that adheres to the given constraints, representing the baseline or reference point. According to the literature, these results approximate the system's current state (Alshqaqeeq et al., 2017; Diano, 2023).

The second and third configurations shall be denoted as *waste reduction* and *cost reduction*, respectively. The former minimizes the food waste, while the latter minimizes the costs associated with the meals. Finally, the multi-objective model employs the perpendicular search technique to simultaneously minimize both objectives. The point where minimal waste and minimal cost meet is an unattainable solution and will be called the *utopian point*. It does not represent a feasible solution. Subsequently, the closest attainable solution to the utopian point, determined via Euclidean distance calculation, shall be regarded as the best trade-off solution and will be called the *multi-objective* setting.

Each computational model generates individualized meals containing precise quantities of diverse food items based on a patient's specific dietary requirements, hospital ward, and food intolerance, for each day of the week. The model precisely crafts dishes (for example, fish with potatoes, rice, and lettuce) by specifying the quantities of each food item. This process ensures a personalized and diverse weekly menu, reflecting the patient's specific dietary needs. The generation of meals involves meticulous consideration of several factors, and the model's ability to specify both the dishes and their respective portions contributes to the creation of tailored, nutritionally balanced menus aligned with individual patient restrictions.

The system provides users with valuable insights about the construction of the meal, the extent of food waste, the meal-building costs, and the distribution of food groups within the meal. Furthermore, users can explore the interactions considered by the mathematical framework, such as searching for a particular patient profile, ward, or diet, and evaluate the corresponding meal composition. Additionally, the model enables users to assess the fulfillment of nutritional requirements for a specific patient profile through appropriate filtering mechanisms.

## 3. Case study

This section provides a case study centered around a 1000-bed hospital located in Florida. The utilized data originates from the 2018 Healthcare Cost and Utilization Project State Inpatient Databases (HCUP SID) (Agency for Healthcare Research and Quality, 2018), including patient demographics in terms of gender and age group. Inferences were made regarding the appropriate medical ward allocation based on the conditions of each patient. Patients diagnosed with cancer were allocated to the oncology ward, those aged 17 and under were allocated to the pediatric ward, patients with orthopedic diagnoses were allocated to the orthopedic ward, and the remaining patients were allocated to the general medicine ward.

Regarding dietary interventions, individuals diagnosed with hypertension and cardiovascular diseases were assigned to the low-sodium diet. The limit in terms of sodium consumption for these patients was obtained from the California Department of Social Services (In-Home Supportive Services Training Academy). Moreover, 3.2 % of adult males and 3.5 % of adult females were assigned to follow the vegetarian diet, as a 2016 National Poll revealed that those are the percentages of vegetarian adults in the US (The Vegetarian Resource Group, 2016). The remaining patients were assigned to follow a regular diet.

Regardless of the diet followed by each patient, the proportion of each food group present in the meal was lower-bounded according to the USDA's guidelines (US Department of Agriculture MyPlate). Moreover, the waste percentage of the food items according to each patient profile was obtained from Gomes et al. (2020).

The model was developed to meet the nutritional and caloric needs of individual patients. In this case study, a set of 25 essential food nutrients was obtained from the NIH Office of Dietary Supplements (2019). This online resource provides information on the minimal requirement of each nutrient for various patient profiles. To identify appropriate food sources to satisfy the specified nutrient requirements, the USDA Food Data Central database was utilized. This database provides comprehensive information on the nutrient composition of different food items. To determine the caloric requirements, data was obtained from the NIH National Library of Medicine (2022). To simulate a typical meal, the daily nutrient and caloric needs were divided by three, assuming a patient consumes three meals per day. The cost per food item was obtained from the USDA Economic Research Service (2023) and the Statista website (Statista).

For this formulation, the elements of each set are presented in Table 1 from the supplemental material. Among the assortment of food items contemplated for this formulation, a subgroup comprising eggs, milk, wheat bread, white bread, and peanut butter was considered to potentially generate intolerance or allergies. Hence, the parameter $a_i$ will take the value 1 when $i$ represents any of these food items, and none of them will be added to the meals in the food intolerance setting $\alpha = 1$.

This model can be replicated across diverse contexts, with the parameters tailored to suit individual requirements.

Furthermore, the vegetarian diet requires the exclusion of animal-derived food items, which make up a large proportion of the items categorized as protein sources. Therefore, the implementation of constraint (16), which promotes diversity in the meals, was employed for all diets except vegetarian.

The parameter $M$ was assigned a value of 25 to prevent the occurrence of $x$ assuming this specific value, thereby avoiding the generation of a meal containing 2.5 kg of food. Conversely, the parameter $m$ was set to 0.05, ensuring a modest value of 5 g, as an excessively low magnitude would lead to the formulation of an impractical meal configuration in the context of food preparation in a hospital kitchen setting.

The mathematical formulation yields customized weekly lunch plans for distinct patient categories, generating over 300 unique meal combinations daily. This diversity arises from the consideration of 14 profiles, 4 wards, 3 types of diets, and 2 food intolerance scenarios. To facilitate analysis, the present study narrows down the 14 profiles to three: adult females, adult males, and children. Therefore, let the following be the case of two patients: a male aged 15 and a female aged 16; both patients fall within the category of "children." According to established guidelines, male patients between the ages of 14 and 18 need a daily intake of no less than 0.9 mg of vitamin A, whereas female patients within the same age range require a minimum of 0.7 mg (National Institutes of Health, 2019). As both patients belong to the same cohort, children, it is imperative that their dietary provisions meet the requirements of both genders. Consequently, both patients' meals will contain a minimum of 0.9 mg of vitamin A.

## 4. Results and discussion

The results were obtained by employing the programming language Julia 1.8.2 and Gurobi 9.5.2 using a Dell Precision 5820 with an Intel(R) Core(TM) i9-10920X CPU @ 3.50 GHz, 128 GB of RAM, and 64-bit Windows 10 Enterprise. The model was implemented on the specified dataset and configurations described in the case study. Notably, a total of 72 meal combinations (three patient profiles, four medical wards, three types of diet, two food intolerance scenarios) were simulated per day to generate weekly lunch meals, encompassing diverse food options.

The baseline setting determined the total amount of waste generated by the hospital within a weekly timeframe, resulting in 501.80 kg. This translates to approximately 28.76 tons of annual waste, which aligns closely with the literature citing a value of 29 tons per year (Alshqaqeeq et al., 2017). The cost obtained for this setting is \$7,794.77 per week, and \$405,328.04 in a year.

Subsequently, the waste and cost reduction models presented the following weekly results: 388.74 kg of food waste and a cost of \$6,282.51 for the waste reduction model and 439.71 kg of food waste and a cost of \$4,911.01 for the cost reduction model.

Finally, the multi-objective setting was implemented. Fig. 1 illustrates the non-dominated frontier for the food waste and the associated cost of meal construction in the multi-objective setting. The curve contains a finite set of 787 feasible solutions that optimize the trade-off between the two objectives. However, as previously noted, attaining the utopian point is unfeasible. Hence, from all the points in the non-dominated frontier, the multi-objective setting was determined by the best trade-off solution, calculated with the minimum Euclidean distance to the utopian point, as outlined in Rossit et al. (2021), and Deshpande et al. (2013). The variables were normalized to account for the distinct units of measurement employed (kilograms and dollars). The results obtained for this solution are 402.96 kg of food waste and a cost of \$5,249.15 per week. However, the selection of the best trade-off solution is contingent upon the specific conditions and requirements of the analyzed system.

Compared to the baseline, the waste reduction setting exhibits a decrease of 113.06 kg in food waste and cost savings of \$1,512.26 per week. Similarly, the cost reduction setting yields savings of \$2,883.76, while reducing food waste by 62.09 kg per week compared to the baseline. Notably, the multi-objective setting mitigates both food waste and cost, exhibiting 98.84 kg of food waste reduction and savings of \$2,545.62 per week.

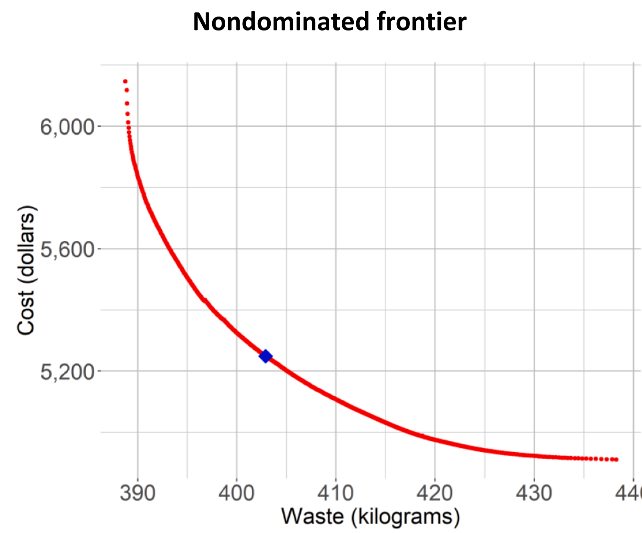


**Fig. 1.** The curve shows all optimal solutions when minimizing the two objectives: food waste and meal-building costs.

Over the course of a 12-month period, the baseline setting is estimated to produce 26,093.60 kg (equivalent to 28.76 tons) of food waste, the waste reduction setting 20,214.48 kg (22.28 tons), the cost reduction setting 22,864.92 kg (25.20 tons), and the multi-objective setting 20,953.92 kg (23.10 tons). Compared to the baseline, the multi-objective setting demonstrates a reduction of 5,139.68 kg (5.66 tons) in annual food waste.

Likewise, the expenses associated with meal construction within the span of 1 year are estimated to amount to \$405,328.04 for the baseline setting, \$326,690.52 for the waste reduction setting, \$255,372.52 for the cost reduction setting, and \$272,955.80 for the multi-objective setting. This last setting presents annual savings of \$132,372.24 in contrast to the baseline. The values of food waste (kilograms) and cost (dollars) obtained per meal are aggregated for each setting in Table 1. Since patients have different profiles, the table provides the average results and includes the standard deviation as a reference of the variability.

Table 2 presents a comprehensive analysis of food waste generation per meal across various wards and diets. There are different patient profiles under each ward and diet, e.g., under the medicine ward, there are male and female patients who follow different diets and have different food intolerance conditions. Therefore, the table provides the mean and the standard deviation representing the central tendency and the variability on the food waste and the meal-building costs. All wards and diets within the multi-objective model exhibit improvements in food

**Table 1**
Minimum waste and cost for each setting.

| Setting | FW per meal (kg) | | Cost per meal (\$) | |
|---|---|---|---|---|
| | Avg | SD | Avg | SD |
| Baseline | 0.16 | 0.03 | 2.53 | 0.65 |
| Waste reduction | 0.13 | 0.02 | 2.04 | 0.56 |
| Cost reduction | 0.14 | 0.03 | 1.59 | 0.56 |
| Multi-objective | 0.13 | 0.02 | 1.70 | 0.60 |

Abbreviations: FW = food waste; kg = kilograms; \$ = dollars; Avg = average; SD = standard deviation

**Table 2**
Waste per meal (kg) among the different wards and diets.

| Ward/diet | Baseline | | Multi-objective | |
|---|---|---|---|---|
| | Avg | SD | Avg | SD |
| Medicine ward | 0.16 | 0.02 | 0.13 | 0.02 |
| Oncology ward | 0.16 | 0.03 | 0.13 | 0.02 |
| Orthopedic ward | 0.17 | 0.03 | 0.14 | 0.02 |
| Pediatric ward | 0.20 | 0.03 | 0.16 | 0.01 |
| Low-sodium diet | 0.16 | 0.02 | 0.13 | 0.02 |
| Regular diet | 0.17 | 0.03 | 0.14 | 0.02 |
| Vegetarian diet | 0.19 | 0.02 | 0.13 | 0.02 |

Abbreviations: kg = kilograms; Avg = average; SD = standard deviation.

waste reduction compared to the baseline scenario. Notably, in both the baseline and multi-objective settings, the medicine and oncology wards exhibit the lowest food waste production, and the pediatric ward the highest. Furthermore, in the baseline scenario, the vegetarian diet generates the highest food waste, while the low-sodium diet yields the least waste. Conversely, in the multi-objective context, the low-sodium diet results in the least and the regular diet in the most food waste.

Table 3 provides a detailed breakdown of the expenditure per meal incurred by each ward and diet in the multi-objective and baseline settings. Once again, the multi-objective model demonstrated cost savings when compared to the baseline for all wards and diets. Among the wards, orthopedics incurs the highest meal-related expenses and the pediatric ward the lowest. In the baseline scenario, the vegetarian diet produces the highest meal-building costs and the regular diet with the lowest. Conversely, in the multi-objective setting, the vegetarian diet has the lowest meal-related costs while the low-sodium diet the highest. Fig. 2 provides a visual representation of the improvement observed in the multi-objective setting for reduction of food waste and meal-building costs per ward and diet compared to the baseline.

The figure reveals analogous patterns of waste and cost reduction in the medicine, oncology, and orthopedic wards. However, the pediatric ward exhibits the least reduction in cost and the most significant decrease in waste. This outcome can be attributed to the large food waste generated in this ward under baseline conditions, which provides the greatest potential for improvement. In contrast, the cost reduction possibilities appear limited given the already low cost on this ward. The results shown in the graph for the low-sodium and regular diets are similar. In contrast, the vegetarian diet exhibits the largest reduction in both variables. This outcome might be because the vegetarian diet has the highest food waste and cost in the baseline setting, which offers the greatest potential for improvement.

The models facilitate a comprehensive examination of the intricate aspects pertaining to the macro-nutrients contained in the meal, adjusted to each specific profile. Table 4 presents the averages for the food waste, meal-building costs, and the food waste costs per macro group in a week.

Vegetables constitute the macro group that incurs the highest food waste and cost. This may be due to the high proportion of vegetables served across the various diets, particularly the vegetarian diet. Additionally, protein-rich foods have the smallest quantity of wasted food. However, the macro group with the lowest meal-building cost and food waste cost is fruit and not protein. This could reflect patients' preferences. Furthermore, the meals within the scenarios that incorporate food intolerance show the highest cost and food waste.

**Table 3**
Cost per meal ($) among the different wards and diets.

| Ward/diet | Baseline | | Multi-objective | |
|---|---|---|---|---|
| | Avg | SD | Avg | SD |
| Medicine ward | 2.55 | 0.66 | 1.73 | 0.62 |
| Oncology ward | 2.54 | 0.67 | 1.70 | 0.59 |
| Orthopedic ward | 2.60 | 0.65 | 1.74 | 0.64 |
| Pediatric ward | 2.26 | 0.53 | 1.63 | 0.63 |
| Low-sodium diet | 2.55 | 0.66 | 1.74 | 0.63 |
| Regular diet | 2.42 | 0.65 | 1.66 | 0.59 |
| Vegetarian diet | 2.89 | 0.29 | 1.55 | 0.46 |

Abbreviations: $ = dollars; Avg = average; SD = standard deviation.

The framework also enables the investigation of patient subgroups by considering individual parameters. Specifically, when analyzing each profile, it is feasible to obtain key metrics such as the average weight and the corresponding costs for the food served and the food wasted. This can be observed in Table 2 from the supplemental material.

Notably, the average meal for the children group results in the highest amount of waste in weight and cost. This is unsurprising given the common tendency among children to be more selective in their food preferences, which contributes to increased waste. It also relates to the fact that the pediatric ward exhibits the highest waste generation. However, the meal for adult females (aged 19 years and above) is found to be the most expensive, probably due to the differing nutritional requirements between genders. Specifically, females between the ages of 50 and 70 require a higher calcium intake compared to males in the same age range, while women aged 19 – 50 require more iron than males. Regrettably, certain food items that are rich in calcium and iron tend to be more expensive than most food items.

Moreover, the results reveal that 35.43 % of the children's food is wasted, which accounts for 35.35 % of the meal's cost. Likewise, 28.62 % of female adults' food is wasted, representing 28.68 % of the meal's cost. Similarly, male adults waste 27.57 % of their meal weight, which corresponds to 27.42 % of the meal's cost.

The intake is the difference between the food served and the food wasted, and is 363.40 g for children, 418.03 g for adult females, and 391.41 g for adult males. Therefore, children consume less than adults.

The dataset described in the case study was used to obtain the proportions of patients belonging to each configuration, which were extrapolated to accommodate the patient demand corresponding to a 1000-bed hospital. The patient counts associated with each type were rounded to the nearest whole number, and in numerous instances, the proportions were insignificantly small, thereby approximating zero. Consequently, of the 36 patient configurations considered, only 17 present patient demand in this case study. Table 3 from the supplemental material document lists these 17 types of patients.

Fig. 3 presents the improvement in waste reduction for each of the 17 patient categories, as compared to the baseline, across different settings. Configurations 10 and 17 exhibit the most substantial reduction in waste across all settings. These configurations comprise adult patients in the medicine ward who adhere to the vegetarian diet. The rationale behind this improvement stems from the fact that in the baseline scenario the vegetarian diet contributes the most to food waste generation compared to the other diets. Therefore, it is reasonable to anticipate greater potential for improvement in these settings. Considering that the oncology ward generates the highest amount of food waste, it could be hypothesized that a configuration consisting of adult females in the oncology ward following a vegetarian diet would yield the greatest reduction. However, in the current case study that configuration does not have a significant demand. It is important to note that there is no configuration with demand composed of children following a vegetarian diet assigned to the medicine or oncology wards in this case study. Logic suggests that if such configuration presented demand, it would belong to the ones generating the most food waste.

The subsequent configuration that exhibits the most waste reduction is 3, which consists of children adhering to the vegetarian diet in the pediatric ward, which is the only ward that contains children following the vegetarian diet in this case study. To summarize, the three configurations involving the vegetarian diet demonstrate the highest levels of waste reduction. This observation implies an influence of the patient's diet on the proportion of waste that can be minimized with the proposed model.

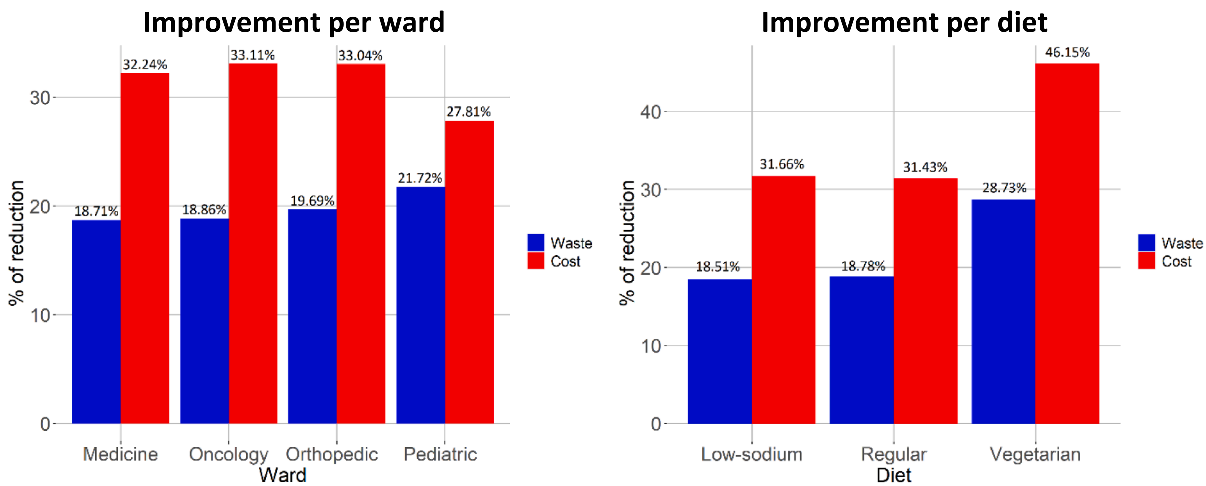


**Fig. 2.** The graph displays the percentages of waste and cost reduced per ward and diet when comparing the multi-objective setting to the baseline.

**Table 4**
Waste weight and cost per food group.

| Macro | Waste (kg) | Meal cost ($) | Waste cost ($) |
|---|---|---|---|
| Vegetables | 137.87 | 2195.74 | 639.42 |
| Fruits | 66.23 | 406.41 | 117.65 |
| Protein | 32.27 | 467.90 | 125.21 |
| Dairy | 124.48 | 1211.78 | 348.59 |
| Grain | 42.11 | 967.32 | 283.85 |
| Total | 402.96 | 5249.15 | 1514.72 |

Abbreviations: kg = kilograms; $ = dollars.

It can also be observed that among the various configurations examined, configurations 3, 17, and 10, demonstrate the most pronounced reduction in meal-building costs across all settings compared to the remaining profiles. Remarkably, these three configurations are the ones that exhibit the most substantial decrease in generating waste. All three configurations correspond to a vegetarian diet, which is associated with the highest meal-building costs. Again, it is evident that the patients' diet significantly impacts the reduction in meal-building costs.

Expanding on the practical implications of the framework in hospital kitchen management, this research underscores a substantial improvement in operational efficiency. The model not only excels in accurately estimating the required quantities of each food item for the upcoming week, directly addressing inefficiencies in the ordering process; it goes a step further by empowering kitchen professionals with detailed guidance on how to craft meal plans efficiently.

This enhancement simplifies the planning and ordering operations, and improves resource utilization. The detailed instructions provided by the model, specifying both the diverse and nutritionally balanced dishes tailored to individual patient constraints and the exact quantities of each ingredient required for every meal, contribute to minimizing waste and optimizing resource allocation. Furthermore, the provision of food to patients and associated levels of waste are often a priority focus on hospital cost management (do Rosario and Walton, 2020); hence, the implementation of the model will add value in the real context of kitchen management.

## 5. Conclusions and future directions

Optimization of the meal construction process positively impacts the framework of healthcare food service operations from the financial, waste-reduction, and nutrition-enhancement perspectives. To the best of our knowledge, this is the first study that employs MIP and a multi-objective approach to reduce food waste and the costs associated with preparing food servings in a hospital.

The study reveals that the pediatric ward has the highest food waste per meal (0.2 kg), leading to a 20 % reduction. Children are eating on average 41.32 g less than adults, and their food servings generate 35.43

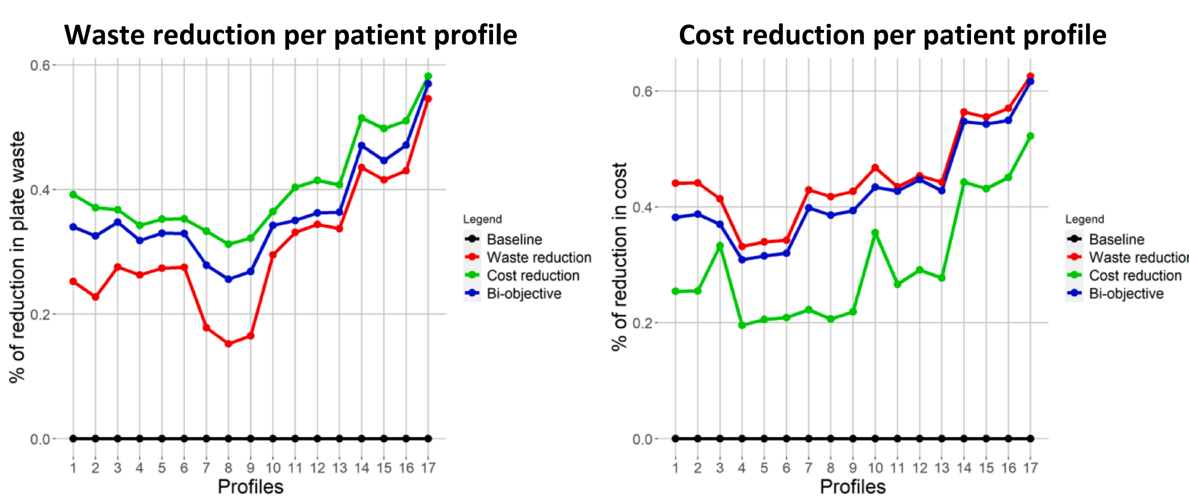


**Fig. 3.** The graph illustrates the percentage of reduction in food waste and in meal-building costs per profile and when comparing each setting to the baseline.

% of waste. This suggests that children may not be receiving the appropriate nourishment, which may require more effective food management strategies for them.

Moreover, the vegetarian diet exhibits the highest levels of wasted food and meal-building costs. Nevertheless, this diet showcases the most significant improvements in both of these aspects when applying the multi-objective model. Remarkably, up to 19.70 % reduction in food waste and 32.66 % in cost are achieved through this intervention.

Based on the findings of this study, the proposed mathematical framework can reduce food waste by approximately 22.53 %. This translates to an estimated weekly waste reduction of 113.06 kg in a 1000-bed hospital.

The optimization models employed in this study possess inherent flexibility, enabling their adaptation to various contexts, including alternative hospital wards, diverse dietary restrictions, fluctuating demands, and alternative food item selections for constructing the meal. Even though there may be computational challenges depending on the array of options considered for each parameter, the model ran multiple scenarios with a wide variety of food items. To the best of our knowledge, it aligns with real-world demands (Johns Hopkins Medicine, 2023) without compromising efficiency.

Moreover, the present study offers valuable insights into the behavioral patterns exhibited by distinct categories of patients. By determining the individuals who are predisposed to generate higher levels of waste, practitioners can enhance their plans for nutritional care, improving the overall well-being and health outcomes of their patients.

The methodological framework proposed for building meal compositions minimizes costs and food waste while simultaneously meeting the specific nutritional and caloric requirements of various patient categories. The model generates standard meals based on real-world data, making the integration of this approach into a patient's routine seamless. This experience extends beyond individual patients to include kitchen professionals who play a vital role in implementing the model. From the perspective of kitchen professionals' routines, the model is designed to be efficient and supportive. It aids in planning diverse, nutritionally balanced menus without the need for meticulous oversight. The inclusion of practical constraints, such as avoiding the repetition of proteins within a meal and in consecutive days to account of food variety, as outlined in (Guala and Marenco, 2020), further enhances our model's applicability and ease of use in real-world hospital kitchen settings.

The present case study examined the average patient demand in a week at a 1000-bed hospital in Florida. However, patients' demand may vary across weeks, suggesting the need for future research to analyze diverse scenarios incorporating stochastic demand and parameters. Finally, a comprehensive understanding of the factors contributing to food waste in healthcare facilities is crucial to develop effective strategies to minimize waste generation and enhance nutrition for patients.

## 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

The data that has been used is confidential.

## Appendix A. Multi-objective optimization

A multi-objective optimization model can be formulated as:

$$\min_{x \in X} F_1(x),\ F_2(x), \cdots, F_n(x), \tag{1}$$

Where $F_k(x)$ is the linear objective function of entity $k$, from $k = 1, \cdots, n$and $X$ represents the feasible set in the decision space (Acuna et al., 2022).

A feasible solution $x' \in X$ is called efficient if there is no other $x \in X$ such that $F(x) \geq F(x')$ for $k = 1, \cdots, n$ and $F(x) \neq F(x')$. If $x'$ is efficient, then $F(x')$ is called a nondominated point. The set of all nondominated points $F(x') \in Y$ for some $x' \in X_E$ is referred to as the nondominated set or efficient frontier (Ehrgott, 2005). For this study, the multi-objective model minimizing the food and the waste was solved using the perpendicular search method, which utilizes a search direction that is always perpendicular to the parameter axis. Using this method, one parameter changes at a time, while all other parameters keep the same value (Acuna et al., 2020).

### A.1. Mixed integer programming formulation

The present model takes into account both continuous and binary variables, leading to an MIP problem. A mixed-integer program can be formulated as follows:

$$\min_{x \in X,\, y \in Y} cx + hy) \tag{2}$$

$$s.t.\ Ax + Gy \leq b \tag{3}$$

$$x \geq 0 \tag{4}$$

$$y \in \mathbb{Z}^{+}, \tag{5}$$

where $A$ and $G$ are matrices of dimensions $(mxn)$ and $(mxp)$, respectively. Similarly, $c$ and $h$ are row-vectors of size $n$ and $p$, respectively. Additionally, $b$ and $x$ are column-vectors of size $m$ and $n$, where the latter consist of continuous variables. Finally, $y$ is a $p$ column-vector of integer variables (Wolsey, 2020).

### A.2. Limitations

Solving the multi-objective problem to obtain the Pareto front can be computationally demanding, particularly when considering that the quantity of food can be adjusted to as little as 5 grams per food item. This results in a significantly higher number of combinations to study, further adding to the computational complexity. In this work, where the focus was on exploring solutions without computational constraints, the model was run on a server with 128 GB of RAM to obtain the full nondominated frontier, consisting of 787 non-dominated points.

**Table A.1**
Sets, parameters, and decision variables.

| Attributes | Notation | Definition |
|---|---|---|
| Set | $I$ | Set of food items, where each element is represented by $i$ |
| Set | $\Omega$ | Set of wards, where each element is represented by $\omega$ |
| Set | $D$ | Set of types of diets, where each element is represented by $\sigma$ |
| Set | $P$ | Set of patient profiles, where each element is represented by $\rho$ |
| Set | $U$ | Set of food nutrients, where each element is represented by $\mu$ |
| Set | $S$ | Set of food groups, where each element is represented by $\tau$ |
| Set | $V$ | Set of food intolerance scenarios, where each element is represented by $\alpha$ |
| Set | $\Delta$ | Set of days of the week, where each element is represented by $\delta$ |
| Parameter | $p_i$ | Calories contained in a gram of food item $i$ |
| Parameter | $c_i$ | Cost in US dollars per gram of food item $i$ |
| Parameter | $a_i$ | 1 if food item $i$ represents a common allergy or food intolerance, 0 otherwise |
| Parameter | $n_{i\mu}$ | Milligrams of nutrient $\mu$ present in a gram of food item $i$ |
| Parameter | $g_{i\tau}$ | 1 if food item $i$ pertains to the food group $\tau$, 0 otherwise |
| Parameter | $b_\rho$ | Minimum calories for patients with profile $\rho$ in a meal |
| Parameter | $t_\rho$ | Maximum calories for patients with profile $\rho$ in a meal |
| Parameter | $w_{i\omega\rho}$ | Percentage of food item $i$ wasted per patient with profile $\rho$ in the ward $\omega$ |
| Parameter | $r_{\mu\rho}$ | Milligrams of nutrient $\mu$ required for patient with profile $\rho$ in a meal |
| Parameter | $e_{\rho\tau}$ | Minimum proportion of food group $\tau$ required for patients with profile $\rho$ |
| Parameter | $q_{\rho\omega}^{\sigma\alpha\delta}$ | Number of patients with profile $\rho$, ward $\omega$, diet $\sigma$, with food intolerance scenario $\alpha$, for the day $\delta$ of the week |
| Parameter | $F$ | Maximum amount (expressed in grams) of sodium to be ingested by patients following the low-sodium diet |
| Parameter | $m$ | Minimum quantity (expressed in grams) of any food item that may be served upon selection for placement in a meal |
| Parameter | $M$ | Maximum quantity (expressed in grams) of any food item that may be served upon selection for placement in a meal |
| Variable | $x_{i\omega\alpha}^{\rho\sigma\delta}$ | Grams of food item $i$ that should be served to the patient from ward $\omega$, with food intolerance scenario $\alpha$, profile $\rho$, diet $\sigma$, in day $\delta$ |
| Variable | $y_{i\omega\alpha}^{\rho\sigma\delta}$ | 1, if food item $i$ was served to the patient from ward $\omega$, with food intolerance scenario $\alpha$, profile $\rho$, diet $\sigma$, in day $\delta$, and 0, otherwise |

To run the model with fewer computational resources, several alternatives can be considered. These include reducing the precision of the units, limiting the number of solutions explored in the bi-objective approach, or running individual modes per group of patients.

Moreover, this study represents a theoretical approach, and the next step is to bridge this gap between theory and practice. This will involve considering logistical challenges and fine-tuning the model based on the characteristics of the hospital. This process will enhance the practical applicability of the presented approach and contribute to the validation and refinement of the findings of this study in a real-world context.

## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2023.12.010.

## References

Acuna, Jorge A., Zayas-Castro, José L., Charkhgard, Hadi, 2020. Ambulance allocation optimization model for the overcrowding problem in us emergency departments: A case study in florida. Socio-Economic Planning Sciences 71. https://doi.org/10.1016/j.seps.2019.100747. ISSN 00380121.

Acuna, Jorge A., Zayas-Castro, José L., Feijoo, Felipe, Sankaranarayanan, Sriram, Martinez, Rodrigo, Martinez, Diego A., 2022. The waiting game–how cooperation between public and private hospitals can help reduce waiting lists. Health Care Manage. Sci. 25, 100–125. https://doi.org/10.1007/s10729-021-09577-x. ISSN 15729389.

Agency for Healthcare Research and Quality. HCUP State Inpatient Databases (SID) Availability of Data Elements, 2018. URL https://hcup-us.ahrq.gov/db/state/siddist/siddistvarnote2018.jsp.

Alshqaqeeq, Fadhel, Twomey, Janet M., Overcash, Michael, Sadkhi, Anas, 2017. A study of food waste in st. francis hospital. International. J. Healthcare Manage. https://doi.org/10.1080/20479700.2017.1414982. ISSN 20479719.

Amodeo, Demeri E, Klimas, Christie. A life cycle assessment of hospital food waste: A model for large scale commercial impact reduction. *DePaul Discoveries*, 10(1):5, 2021. URL https://via.library.depaul.edu/depaul-disc/vol10/iss1/5.

Coban, Mustafa, Karakas, Filiz, Coban, Nilgun Akbulut, 2023. Quantitative analysis of healthcare waste generation and composition in antalya, turkey. Waste Manage. 160 https://doi.org/10.1016/j.wasman.2023.02.008.

Deshpande, Shubhangi, Watson, Layne T., Canfield, Robert A., 2013. Pareto front approximation using a hybrid approach. Proc. Comput. Sci. 18, 521–530. https://doi.org/10.1016/j.procs.2013.05.216. ISSN 18770509.

Nicole Diano. Writing food menus for hospitals and nursing homes: ensuring food safety, 2023. URL https://menutech.com/en/blog/design-inspiration/writing-food-menus-hospitals-and-nursing-homes-ensuring-food-safety.

Dias-Ferreira, C., Santos, T., Oliveira, V., 2015. Hospital food waste and environmental and economic indicators–a portuguese case study. *Waste management,* 46:146–154, 2015. ISSN 18792456. doi:10.1016/j.wasman.2015.09.025.

Diaz, Luis F, Eggerth, L.L., Enkhtsetseg, S.H., Savage, G.M., 2008. Characteristics of healthcare wastes. *Waste management,* 28(7):1219–1226. doi:10.1016/j.wasman.2007.04.010.715.

Diaz, L.F., Savage, G.M., Eggerth, L.L., 2005. Alternatives for the treatment and disposal of healthcare wastes in developing countries. Waste Management 25 (6), 626–637. https://doi.org/10.1016/j.wasman.2005.01.005.

do Rosario, Vinicius A., Karen Walton. (2020). Hospital Food Service. In Herbert L. Meiselman (Ed.), Handbook of Eating and Drinking (pp. 1007 – 1033). Springer.

Eckelman, Matthew J., Sherman, Jodi. Environmental impacts of the us health care system and effects on public health. *PloS one*, 11(6):e0157014, 2016. doi:10.1371/journal.pone.0157014.724.

Matthias Ehrgott. *Multicriteria optimization*, volume 491. Springer Science & Business Media, 2005.

Hamid El Bilali and Tarek Ben Hassen. Food waste in the countries of the gulf cooperation council: a systematic review. *Foods,* 9(4):463, 2020. ISSN 23048158. doi:10.3390/foods9040463.

Gomes, Ana, Saraiva, Cristina, Alexandra Esteves, and Carla Gonçalves. Evaluation of hospital food waste—a case study in portugal. *Sustainability,* 12(15):6157, 2020.646ISSN 20711050. doi:10.3390/su12156157.

Sebastian Guala and Javier Marenco. Scheduling Weekly Menus in a Hospital with Integer Programming Techniques. *Revista Investigación Operacional*, 41:6779, 2020. URL https://rev-inv-ope.pantheonsorbonne.fr/sites/default/files/inline-files/41120-05.pdf.

Md Lokman Hossain, Md Jaseem Uddin, et al. Medical waste management at upazila level in bangladesh. *Journal of Environmental Treatment Techniques*, 2(3):85–94, 2014. URL http://www.jett.dormaj.com.

In-Home Supportive Services Training Academy, California Department of Social Services. *Types of therapeutic diets*. URL https://www.cdss.ca.gov/agedblinddisabled/res/VPTC2/9%20Food%20Nutrition%20and%20Preparation/Types_of_Therapeutic_Diets.pdf.

John Hopkins Medicine. Patient Meals. URL https://www.hopkinsmedicine.org/patient-care/patients-visitors/admission-discharge/patient-meals.

Karen Kuperberg, Angelina Caruso, Susan Dello, and Diana Mager. How will a room service delivery system affect dietary intake, food costs, food waste and patient satisfaction in a paediatric hospital? a pilot study. *Journal of Foodservice,* 19(5): 255–261, 2008. ISSN 17480140. doi:10.1111/j.1748-0159.2008.00103.x.

Manfred Lenzen, Arunima Malik, Mengyu Li, Jacob Fry, Helga Weisz, Peter-Paul Pichler, Leonardo Suveges Moreira Chaves, Anthony Capon, and David Pencheon. The environmental footprint of health care: a global assessment. *The Lancet Planetary Health*, 4(7):e271–e279, 2020. doi:10.1016/S2542-5196(20)30121-2.

Bontle Mbongwe, Baagi T Mmereki, and Andrew Magashula. Healthcare waste management: current practices in selected healthcare facilities, botswana. *Waste management*, 28(1):226–233, 2008. doi:10.1016/j.wasman.2006.12.019.

McCray, Sally, Maunder, K., L Barsha, Mackenzie-Shalders, Kristen. Room service in a public hospital improves nutritional intake and increases patient satisfaction while decreasing food waste and cost. *Journal of Human Nutrition and Dietetics*, 31(6): 734–741, 2018. ISSN 1365277X. doi:10.1111/jhn.12580.

Michlowicz Edward. Optimization of nonlinear transport-production task of medical waste. *Archives of Transport*, 24(3):353–366, 2012. ISSN 08669546. doi:10.2478/v10174-012-0022-4. URL https://bibliotekanauki.pl/articles/224120.pdf.

Minoglou Minas, Spyridoula Gerassimidou, and Dimitrios Komilis. Healthcare waste generation worldwide and its dependence on socio-economic and environmental factors. *Sustainability,* 9(2):220, 2017. ISSN 20711050. doi:10.3390/su9020220.

National Institutes of Health. *Dietary reference intakes (DRIS): Recommended dietary allowances and adequate intakes, elements*, 2019. URL https://www.ncbi.nlm.nih.gov/books/NBK545442/table/appJ_tab3/?report=objectonly.

National Institutes of Health. *Nutrition and hydration requirements in children and adults*, 2022. URL https://www.ncbi.nlm.nih.gov/books/NBK562207/.

Kwabena Titi Ofei, Mette Holst, Henrik Højgaard Rasmussen, and Bent Egberg Mikkelsen. How practice contributes to trolley food waste. a qualitative study among staff involved in serving meals to hospital patients. *Appetite,* 83:49–56, 2014. ISSN 10958304. doi:10.1016/j.appet.2014.08.001.

Nurul Huda Razalli, Chui Fen Cheah, Nur Mahirah Amani Mohammad, and Zahara Abdul Manaf. Plate waste study among hospitalised patients receiving texture-modified diet. *Nutrition research and practice*, 15(5):655–671, 2021. ISSN 20056168. doi: 10.4162/nrp.2021.15.5.655.

Rossit, D.G., Rossit, D.A., Nesmachnow, S., 2021. Explicit multiobjective evolutionary algorithms for flow shop scheduling with missing operations. Programmi. Comput. Software 47, 615–630.

Sara Schiavone, Concetta Paola Pelullo, and Francesco Attena. Patient evaluation of food waste in three hospitals in southern italy. *International journal of environmental research and public health*, 16(22):4330, 2019. ISSN 16604601. doi:10.3390/ijerph16224330.

Sonnino, Roberta, McWilliam, Susannah. Food waste, catering practices and public procurement: A case study of hospital food systems in wales. Food Policy, 36(6): 823–829, 2011. ISSN 03069192. doi:10.1016/j.foodpol.2011.09.003.

Statista. URL https://www.statista.com/.

Stefanie Carino, Judi Porter, Shirin Malekpour, and Jorja Collins. Environmental sustainability of hospital foodservices across the food supply chain: a systematic review. *Journal of the Academy of Nutrition and Dietetics,* 120(5):825–873, 2020. ISSN 22122672. doi:10.1016/j.jand.2020.01.001.

Christina Strotmann, Silke Friedrich, Judith Kreyenschmidt, Petra Teitscheid, and Guido Ritter. Comparing food provided and wasted before and after implementing measures against food waste in three healthcare food service facilities. *Sustainability,* 9(8):1409, 2017. ISSN 20711050. doi:10.3390/su9081409.

Synani, K., Abeliotis, K., Terzis, E., Manios, T., Lasaridi, K., 2021. Life cycle impacts of food waste: The case study of hotels in heraklion crete. In: In Proceedings of the 8th International Conference on Sustainable Solid Waste Management, pp. 23–25.

The Vegetarian Resource Group. *How many adults in the U.S. are vegetarian and vegan?*, 2016. URL https://www.vrg.org/nutshell/Polls/2016_adults_veg.htm.

Ali Ebadi Torkayesh, Behnam Malmir, and Mehdi Rajabi Asadabadi. Sustainable waste disposal technology selection: The stratified best-worst multi-criteria decision-making method. *Waste Management,* 122:100–112, 2021. doi:10.1016/j.wasman.2020.12.040.

US Department of Agriculture Economic Research Service. Fruit and vegetable prices, 2023. URL https://www.ers.usda.gov/data-products/fruit-and-vegetable-prices/.

US Department of Agriculture FoodData Central. URL https://fdc.nal.usda.gov/fdc-app.html#/.

US Department of Agriculture MyPlate. URL https://www.myplate.gov/eat-healthy/what-is-myplate.

Williams, Peter, Walton, Karen. Plate waste in hospitals and strategies for change. *e-SPEN, the European e-Journal of Clinical Nutrition and Metabolism,* 6(6):e235–e241, 2011. ISSN 17514991. doi:10.1016/j.eclnm.2011.09.006.

Wolsey, Laurence A.. *Integer programming.* John Wiley & Sons, 2020.