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  Artificial Intelligence for Environmental Risk

MRes project report 2022

Optimising remote field station FOOD PURCHASING

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# Abstract

The British Antarctic Survey’s operations teams are responsible for providing all the resources required to sustain hundreds of people working at Antarctic research stations daily. The food purchasing problem is a large search problem which is currently solved by human experts, but they do not achieve optimal solutions.

The aim of this project was to create a model to suggest meal plans and food purchasing strategies which minimise the associated carbon footprint, financial cost and waste. Constraint-satisfaction programming was used to attempt to model the knowledge of the human operations team and to search the space efficiently.

The output from the model suggests a plan with a possible 16% reduction of global warming potential while satisfying the practical and nutritional constraints. The model offered improvements on all objectives during its runtime. It could be used to help the operations teams plan food purchasing strategies.

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# Introduction

The British Antarctic Survey (BAS) conduct research on a range of important topics including climate change and the natural sciences. Field expeditions to Antarctica facilitate much of this research. BAS operations teams are responsible for providing the resources required to sustain personnel working at Antarctic research stations. The Rothera research station is the largest, regularly housing over a hundred people at once. Demanding work in harsh conditions necessitates that these people eat the best possible diets, and there is no room for oversight when planning their nutritional intake. However, supplying the food is logistically challenging and has a considerable carbon footprint and financial cost. The food purchasing problem is a large search problem which is solved by experienced humans, but they do not achieve optimal solutions.

Dickens (2021) investigated where BAS could improve their carbon footprint, and identified food supply adjustments as having the most potential, because although food at Rothera amounts to around one percent of greenhouse gas (GHG) emissions associated with BAS’ operations, it is easier to change than other things such as shipping schedules, which are more tightly constrained.

This work uses carbon dioxide equivalent (CO2e) to express the global warming potential of GHG emissions associated with actions and objects. Global warming potential (GWP) is used to express the potential effect of choices on GHG emissions and their contribution to climate change, and is used by the Department for Environment, Food and Rural Affairs (2014). CO2e values are estimated based on averages but are universally understood and food production data using this measurement were plentiful.

Artificial intelligence (AI) was used in this project to attempt to model the knowledge of the human operations team and search the space efficiently. Machine learning was not applicable because of the lack of data. The problem was therefore approached as a combinatorial optimisation problem. Modelling and optimisation of constraint-satisfaction problems is a topic of AI in which combinations of parameters are chosen to search for solutions to a given problem, measuring performance by a defined objective (Hooker, 2002).

The aim of this project was to create a model to suggest meal plans and food purchasing strategies which minimise the associated GWP, financial cost and waste.

# Background

Rothera houses 22 to 170 people at once, including a chef who prepares the meals. Movements of people, aircraft and the Sir David Attenborough (SDA) ship are scheduled a year ahead and food orders are made according to this. Food is brought in bulk on the SDA. Because the food needs to last a long time in storage, fresh food is not part of the standard menu, although some is brought by air when there is space available. Food waste is incinerated at Rothera and packaging waste is returned to the UK on the SDA to be handled according to UK waste disposal practices. The team at BAS advised that for this plan, meals would be offered as buffets with a number of options. Some staff stay at the station for 18 months. Due to their long stay in such a bleak environment, their mental health is a serious concern. It is essential for meals to be varied to help prevent boredom.

Although the project’s aim is expressed simply in human language, it is a multi-objective problem which is computationally complex to solve (Dechter, 2003). The program seeks to minimise GWP, financial cost, food waste and packaging waste while maximising the variety of meals and satisfying nutritional requirements, dietary restrictions and delivery schedules. A satisfactory solution could be used to produce a plan for the coming year and its associated food order with measurements of objective performance to help the operations team.

# Methodology

## Communication and organisation

Fortnightly meetings were held between the developer and supervisor. A meeting with BAS was held near the start of the project to agree on the specifications. Meeting minutes are in appendices x to x. A backlog of tasks was based on these requirements to ensure that milestones were met. A Trello board was used for task organisation, and code was held in a GitHub repository. The first three weeks were spent attending a Coursera programme on modelling for discrete optimisation in MiniZinc, delivered by Lee and Stuckey (2016) so that the developer could gain the necessary skills.

## Data and technology

A spreadsheet containing the previous year’s schedules for people and vehicles, and people’s job roles and genders, was provided by BAS. A copy was created with personal information removed to protect identities and ensure the original data remained unchanged. No data related to food purchasing or meal arrangements were available. This meant the developer had no knowledge of where food was purchased, whether there was a budget, the costs or quantities of food items or how meals were organised. There was no information regarding people’s dietary restrictions. Estimates were made for purchasing using a UK supermarket website (Tesco, 2022) and assumptions were made about the structure of meals. It was assumed that three different choices of breakfast, lunch and tea would be offered daily.

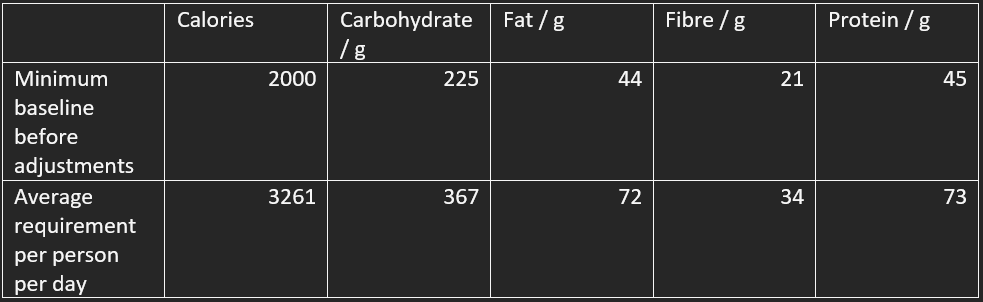
The project follows the principles of Findable, Accessible, Interoperable and Reusable (FAIR) data, defined by Wilkinson et al. (2016). A copy of the schedule data was included in the program files with people's names removed to comply with General Data Protection Regulations (Information Commissioner's Office, 2018). A FAIR data statement was included in the program files (appendix x). Instructions on how to reproduce the results were given in the ReadMe file (appendix x).

MiniZinc is a language created by Brand et al. (2007) specifically for constraint programming and it is the modelling language for this project, with Python for data pre-processing and post-processing. Random dietary requirements were generated for the MiniZinc data. These data were included in the repository so that the results shown could be reproduced.

## Dietary requirements

People’s required nutrition were estimated according to the NHS (2019) who state that requirements depend on age, gender, health, lifestyle, height and other genetic considerations. They state that, typically, men require 25% more calories, with an average daily calorie requirement given as 2000 for women and 2500 for men. All the personnel at Rothera are adults of working age, so it was assumed that age would not be a significant consideration. The physically demanding job roles were important to consider. Boltz (2005) advised that people with the most physically demanding jobs may require double the daily calories they would consume if they had a sedentary lifestyle. Other nutrients must also be scaled up, including carbohydrate, fat, fibre and protein. The NHS (2020) explains that getting enough micronutrients should not be of concern to people who eat a balanced diet because micronutrients are found in abundance in many ingredients. The exception is vitamin D. The NHS (2020) advises that people who do not regularly expose their skin to sunlight take a vitamin D supplement alongside a healthy diet.

To calculate nutritional requirements, baseline figures were defined as the average required by a healthy woman with a mildly active lifestyle. Men were identified from the data and their required amount of each macronutrient was increased by 25%. Job roles were assessed using descriptions from BAS (2015b) and categorised as sedentary, moderately active, with a 50% increase in nutritional requirements, or very active, with a 100% increase in requirements. These labels (appendix x) considered the amount of physical work and the amount of time spent outdoors in the harsh climate. Anyone whose role included field work was classed as very active even if their job role was typically more sedentary. Most personnel were classed as moderately or very active, and an average requirement of 3261 calories per person per day was estimated, as shown in table one.



*Table one - Nutritional requirements.*

Because no information was provided about dietary restrictions, a function was created to append random restrictions to the personnel data to use with the model. Random numbers conforming to a Gaussian distribution assigned numbers of people per group who should not be given meals containing any combination of meat, milk, egg, seeds, nuts, gluten and sugar. The probability of each of these was around 0.1 which was deliberately higher than in the general British population, with approximately one percent of people being vegan, according to Ipsos (2019) and around three percent of people having an allergy to any of the listed ingredients, according to Food Standards Agency (2020), to ensure robustness of the program. This takes into account vegetarian and vegan diets, allergies and intolerances, and diabetes. Other considerations include religious diets, but it was decided with BAS that since a variety of meats and vegan foods would be offered, this would not likely become a problem. Red meat, white meat and fish could be included in the list if necessary. Alcohol was not included in this list because it is an optional treat. It was important to confirm that people with any dietary restrictions could eat a varied diet. Table two shows an example of a meal plan and which options would be available to some people. Person A is vegan. They could choose porridge for breakfast, and two of the three options for lunch and tea, and both side dishes. Person B cannot eat gluten. They can choose two of the three options for breakfast, lunch and tea, and both side dishes. Person C represents the worst case. They can eat a selection of foods. Side dishes helped to ensure that all personnel could eat as much as they wish. If there are no people with a certain restriction, the model is not obligated to satisfy that restriction.



*Table two - Typical daily buffet and its consequences for dietary restrictions.*

An anticipated problem with the buffet arrangement was that all the servings of an option might be taken by people at the front of the queue, leaving only unsuitable options for those who arrive later. This problem is not specific to this project and could occur at any buffet. One option is to prepare more servings to create a surplus, but this could increase food waste. Another option is to provide everyone with a set meal and no choice, but this would be restrictive. A less extreme option would be to provide a menu so people could select their meals and the chef would know how many servings to prepare. Doing this daily would introduce the risk of running out of ingredients, as exact amounts could not be ordered a year ahead. This could be tackled by providing a future menu and asking for meal selections a year ahead, giving the operations team time to order the food and reducing waste.

Regarding the specification for a buffet, the approach taken in this project to reduce food waste and the risk of running out of options was to prepare larger batches of meals, so rather than preparing three different meals for lunch and another three for tea, three different meals would be prepared daily and offered for both lunch and tea. Since there are three options spread over two mealtimes, people should not be forced to eat the same dish twice in a row. This takes into consideration that there is sometimes only one chef for the entire group, which is a demanding job.

The plan includes breakfasts, main meals, side dishes, desserts and occasional treats. Occasional treats were requested by BAS to improve morale and include a snack and an alcoholic beverage, and should not contribute to nutritional calculations but should be included in the order. The set frequency for treats was weekly. Although plant-based diets are associated with reduced GWP, and research by Röös and Rysselberge (2021) supports this, BAS advised that some personnel were unwilling to adopt a plant-based diet. The program therefore offers a variety of meats.

## Transport

Most food is brought to Rothera from the UK yearly on the SDA. Dash-7 aircraft make frequent deliveries of equipment, passengers and fresh food, from South America and the Falklands (BAS, 2021a). The data show that there was no scheduled transit in the winter, so the program does not allow fresh foods to be included during winter.

To estimate the GWP and costs of food transport, assumptions were made in the absence of specific data (appendix x). For the SDA, the capacity for food was assumed to be the total cargo capacity minus the fuel storage capacity, from BAS (2021b). The voyage was assumed to take 20 days from the UK to Rothera. The emissions and fuel consumption were taken from average cargo ship consumption from Tiseo (2021) but this is not accurate because the SDA is a multi-purpose vessel. UK fuel prices were applied. The cost and emissions of moving 100g portions of food were estimated from the overall cost of the journey, one-way, divided by the number of 100g portions that could be transported.

For the Dash-7 aircraft, it was assumed that the journey is direct from the Falklands to Rothera. This distance means the aircraft could not travel fully loaded. The loading capacity was taken from Frawley (1995). The average number of people per flight was calculated from the personnel data. The average mass of British men in Antarctic attire was subtracted from the carrying capacity along with the required extra fuel. The emissions and fuel consumption were taken from Campbell (2022) and the cost of aviation fuel in the UK was applied.

Realistically, neither the SDA nor the Dash-7 would travel with their entire cargo capacity full of food, but this was theoretically assumed so that a proportional comparison could be made. Journeys were considered one-way because the vehicles may return via other research stations with waste, equipment and passengers.

## Practical considerations and assumptions

It was not known where BAS purchased food, so Tesco (2022) was used to get comparative costs, quantities, packaging and nutrition of ingredients. It is likely that BAS buy ingredients in bulk and the cost and packaging waste are less. Values for frozen foods were based on running costs and emissions for UK domestic freezers, for 100g portions of ingredients. It was assumed that non-refrigerated ingredients would be kept in a heated building to prevent them from freezing. Barreneche et al. (2015) showed that the energy required for cooling is typically more than the energy required for heating a space, and the ambient temperate has little effect on the energy cost of cooling, but larger spaces are usually heated so the overall requirement is usually higher for heating. Energy costs were taken from the cost of electricity in the UK, which is not accurate for Rothera, which uses petrol generators and solar panels, but it should still be possible to draw relative comparisons. People in the Arctic have stored frozen food for up to a year in cellars dug into permafrost which could maintain low enough temperatures year-round (Brown et al., 2017). This method requires no electricity and has a smaller cost and GWP than electric refrigeration. Although summertime temperatures at Rothera can stay above 0°C for several weeks, there is permafrost (Baio et al., 2014) so perhaps BAS could explore this option.

Cooking costs and emissions were calculated based on cooking times and methods and the number of portions to be cooked at once. As explained by Janestad et al. (2003) the energy required for oven cooking does not increase linearly with cooking time due to the hot air being insulated inside the oven. The GWP of cooking was found to be so negligible compared to production, transport and storage that it was not useful to consider, but the financial cost was included.

Packaging waste could be viewed from the perspective of the environmental effects of disposal methods and the risk of waste travelling into the oceans, or it could be viewed from the logistic perspective of the cost and emissions of its transportation. It was assumed that packaging waste would be returned on the SDA on its return journey after the food delivery, and because this would leave the SDA with a large available capacity, it was determined more useful to consider the disposal methods. The focus was on non-recyclable packaging. Non-recyclable packages with and without their contents were weighed and masses of packaging were estimated for different ingredients per kilogram of ingredient (appendix x). It was assumed that some recyclable packaging would end up in landfill or become lost (Greenpeace, 2021) so a penalty was included for recyclable, non-biodegradable packaging.

## Constraint modelling

When modelling the constraints of the program, the aim was to capture the conditions usually communicated by human language and embed the reasoning of the operations team in the model. Fixed requirements which were uncompromisable, such as the requirement that everybody is provided with enough nutrition, were encoded as hard constraints. Flexible goals, such as the GWP of the food order, were encoded in the objective function as soft constraints. A satisfactory solution satisfies all the hard constraints and offers a reasonable optimisation of the objective function. For a problem of this complexity, the goal is to find the best possible solution but the search space is too large to realistically expect to find it exhaustively (Dechter, 2003). The definitions of constraints can affect the complexity of the program so they should be modelled carefully to avoid intensive loop kernels, although these are sometimes necessary. Several nested loops were required and splitting data into separate arrays and iterating over each one individually was more suitable than combining them all into one loop.

The model was developed on a week of dummy data for 25 people. The meals and number of portions of each option were chosen for each day. When the real data were added, it became computationally costly for options to be assigned in this way as the number of days and people increased. To simplify this, the model chose one week of meals, as in the earlier version. That weekly menu was repeated throughout the period, adjusting the number of servings of each meal daily according to the personnel data.

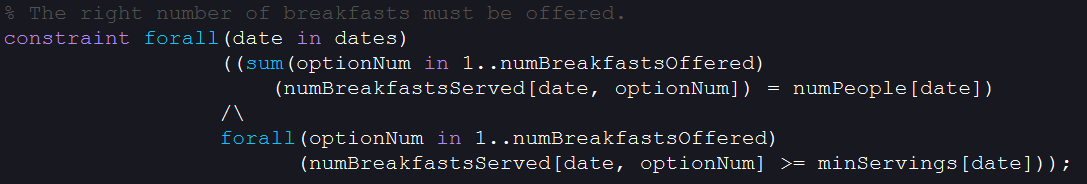
Breakfasts and main meals were considered essential and contained the largest quantities of food so to ensure adequate nutrition and reduce food waste, the number of servings of these was constrained to be equal to the number of people present. Side dishes, desserts and treats were considered non-essential, so the number of servings of these were allowed to vary to give the model some freedom to find different solutions.

Without constraints to introduce variety, one or two recipes were continuously repeated. Constraints were set so that all meal options must be different throughout the week. For breakfasts and main meals, constraints were set to ensure that everyone with dietary restrictions could eat something and that there were enough servings of suitable foods.

Because treats would not be served daily, they were chosen for the entire period, not weekly, and then spread out according to the given frequency of treats. This was constrained to prevent the same treats occurring twice in a row. Treats were not included in the daily nutrition plan because their purpose was for mental, not physical, health.

Fresh ingredients are not available in the winter so a constraint was added to prevent fresh foods from being chosen during this time. Fresh eggs were replaced with powdered egg for some meals, but those requiring a distinct egg texture, such as omelettes, were discounted from the winter options.

A minimum number of servings of each meal option was set because otherwise the model chose to offer many portions of one option and few or no servings of the other options at the buffet. The minimum was defined as a proportion of the number of people present. Figure one shows an example of a constraint in the MiniZinc model to ensure that the number of breakfasts served is equal to the number of diners and that at least the minimum number of servings are offered of each option.



*Figure one – Constraint on the number of servings of each daily breakfast option.*

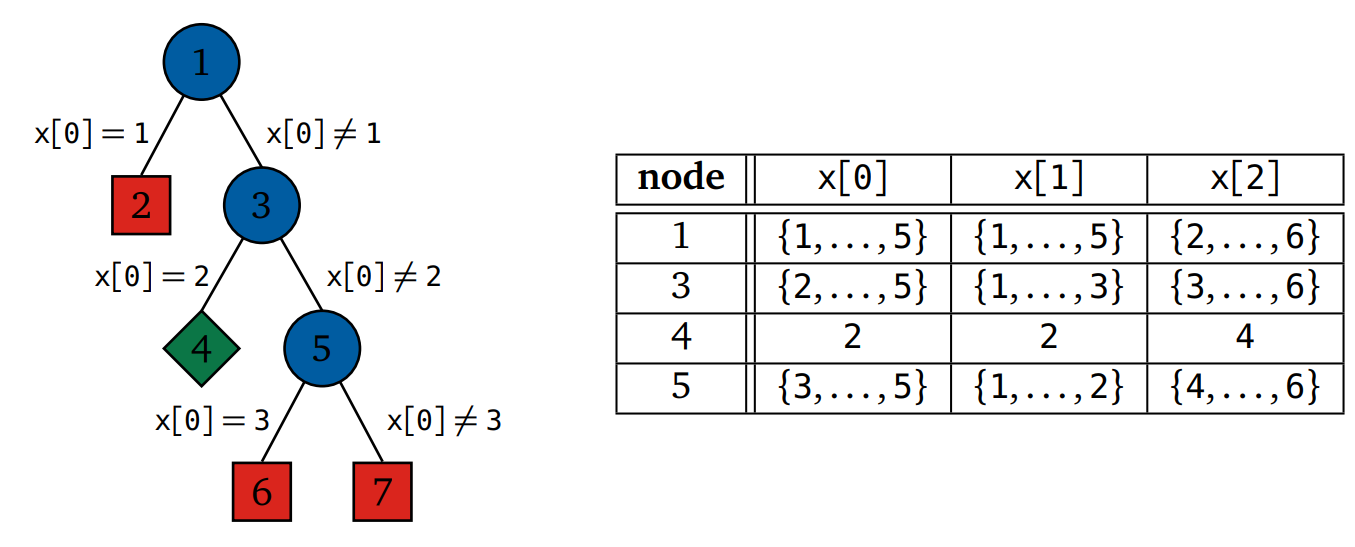
Finally, constraints ensured that personnel were provided with enough of each nutrient daily.

Introducing and tightening hard constraints reduced the number of valid solutions, making the optimisation process faster but restricted to generally worse solutions. A considerable amount of time was spent seeking a balance between solving ability, objective performance and reasonable variety. Improving one of these usually worsened the others. Solving time was not deemed important due to the long-term nature of the application but running the model on a personal computer implied a limit on the complexity in order to receive solutions. To achieve realistic solutions, the variety of meals was implemented as both a hard and a soft constraint. This is an example of why humans must evaluate decisions made by AI before implementing them in the real world (Chen et al., 2021).

Some of the model code appears repetitive because using enumerables for courses was an effective way of processing different meal types but enumerables cannot be passed as parameters in MiniZinc functions. Combining the calculations and constraints into fewer loops with larger kernels and fewer iterations through the complete sets resulted in slower processing.

## Solving technique

Gecode is constraint-satisfaction problem solving software which has performed well at a range of tasks (Stuckey et al., 2014). Gecode interprets the model and data to create a search tree which depends on the constraints. A simple example is shown in figure two. During traversal of the tree, Gecode behaves adaptively and visits nodes up, down and along the tree’s branches, sometimes breaking it up into separate spaces to quickly restore previous positions or to compute sections in parallel. This enables faster searching of large, complex spaces than a simple stepwise algorithm such as a typical depth-first traversal.



*Figure two – Search tree and matrix constructed by Gecode for a constraint that the sum and product of x[0] and x[1] = x[2], from Lagerkvist et al. (2019).*

Gecode was chosen for this project due to its overall success and because it is incorporated in MiniZinc, enabling the human requirements of the application to be prioritised for development. Other solving software, such as Chuffed (Chu et al., 2019), were not compatible with floating point data-types or some operators; Gecode is better able to generalise to a range of data and expressions. It could be useful to investigate other solving software, create a custom search engine using Gecode, or create a search algorithm from scratch designed specifically for this problem. The default technique employed by Geocode was based on an exhaustive traversal through the tree and began at certain positions of each data structure, leading to repetitive, similar results and taking too long to find more varied solutions. Other areas of AI could be used to introduce more randomness and adaptiveness, such as reinforcement learning to trial randomised routes through the tree, or an evolutionary algorithm to refine sequences of parameters, possibly without the need to construct the entire tree (Neumann & Wegener, 2007).

Due to the complexity of the search space and constraints, attempting to solve the problem with the entire 370 days of data resulted in no improvement of the solution over time for at least three hours and was prone to memory overflows. The data were split into smaller batches and the model processed each batch consecutively. The maximum size of each batch was determined so that it contained a matrix of people and days with around 3000 elements. Figure three shows tests to determine the ideal batch size. Tests with data matrix sizes larger than 4000 elements failed to find any solution within 20 minutes. The plot indicates that the model produced consistent results with a variety of data, except when the data were so small that not a full week’s menu was constructed.

*Figure three – Tests on data with different numbers of days and people. Excess food was measured by nutrients above the required amount and has been scaled relatively.*

## Objective function

Various expressions of the objective were tested, attempting to minimise one or a combination of financial cost, GWP, excess food, packaging waste and the lack of variety of meals, which was the difference between the number of servings of each option so that a larger number represented fewer options for the majority of people. Minimising the lack of variety was preferable to maximising variety because all components of the function were positive. Potential food waste was measured as the excess calories and other nutrients above the minimum requirements of the group. Figure four shows how the objective function could be encoded and weighted. The outcomes are similar when values of objectives are scaled to a similar magnitude, which suggests a possible lack of variety of solutions and a need for more flexible constraints, more solving time or a larger range of ingredients. The single-objective functions led to optimisation of only that objective which had little overall effect on the sum of all objectives.

*Figure four – Comparison of performance using different objectives.*

The objective function could not contain floating-point numbers without causing a nonlinear expression or relation error in Gecode, and MiniZinc is strongly typed with static data structures, so the objective function was restricted to addition of integers with little opportunity for scaling. A benefit of this was the small memory space requirement during runtime. Some values were later scaled in the output to match sensible units. It could have been useful to be able to normalise all the values which comprised the objective function and multiply them instead of summing them. This would allow the developer to start with an unbiased objective, with the opportunity to include deliberate, specific weights to variables. Summing and not normalising the objectives creates the risk of variables with large values being prioritised over those with smaller values, which may never be optimised. To reduce this risk, units were manipulated in the data files to produce variables of similar magnitudes.

Finally, the objective function chosen was the sum of financial cost, associated emissions, excess food, packaging waste and the lack of variety of meals, because although this did not perform the best on any one objective, it captured the genuine requirements of the application. With this objective function and the chosen batch sizes, initial solutions were usually produced within 90 seconds and solutions ceased to regularly improve after about four minutes (appendices x to x).

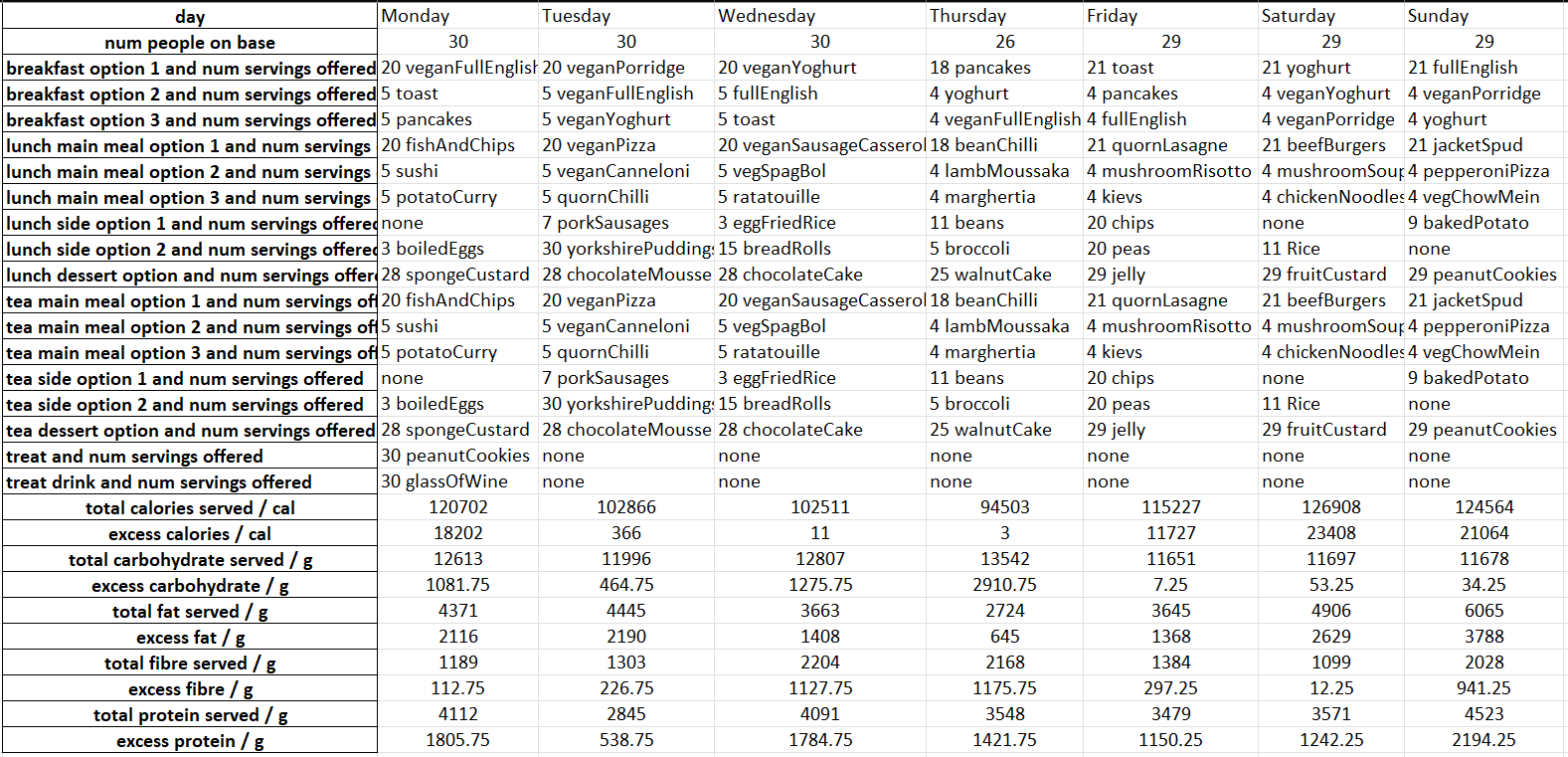
The program is complex because it contains five objectives and variety is inversely related to the other objectives. Having too many objectives, particularly inversely related ones, can reduce performance because the optimisation of each variable may be sacrificed to produce a solution near the middle of the pareto front of equally performing solutions, or one objective may dominate the others, to find a position at one end of the pareto front (MATLAB, 2016).

# Results & discussion

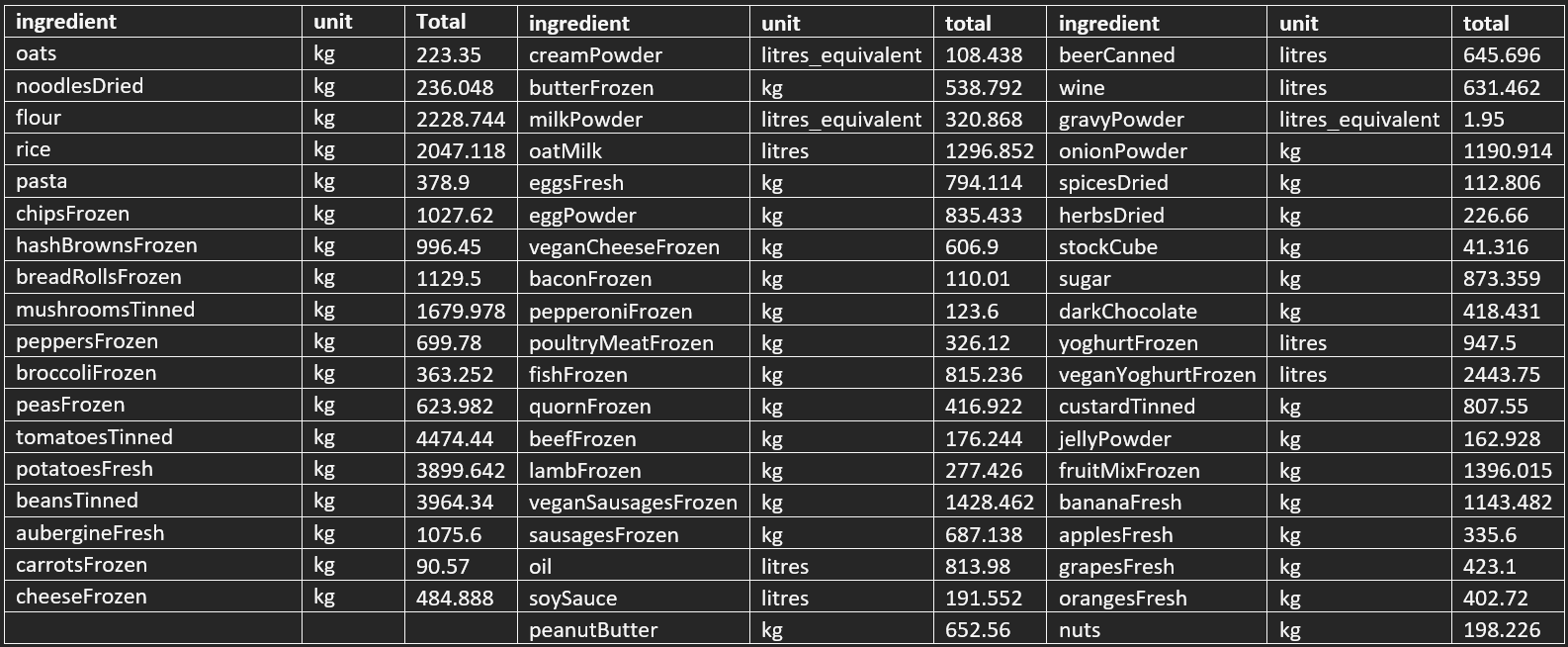
Figures five and six show a comparison of implementing different diet types. The priority is reducing beef and lamb because they are associated with the highest GWP from production (Röös and Rysselberge, 2021). As animal products are reduced, waste decreases. This could be because animal products contain more calories, fat and protein than vegetables so have more potential to waste nutrients. A benefit of this is that they more easily satisfy the high nutritional demand. Some vegetables were assumed to be bought without packaging, which is likely the reason for the reduction in waste as the diet shifts to more vegetable-based meals. There is a slight increase in cost for vegetarian and vegan diets, possibly due to the high cost of animal alternatives and the need for larger quantities of food to satisfy nutritional requirements. There was a slight reduction in emissions for winter meals - 0.5kg CO2e per person per day on average - when no flights were scheduled, but it was not considered useful to discuss this further because flight schedules are unlikely to be adjustable based on this. There is a risk of bad weather delaying flights so the menu is not reliant on aircraft. All essential meals are made from bulk ingredients. There was a small reduction in GWP as animal products are phased out, which is possibly not larger because most meals which the model chose in the meat-containing versions were vegetable-based anyway to satisfy dietary restrictions and minimise GWP. To test this, a version was run with more animal-based meals, no dietary restrictions and no objective and compared with the optimised version of the full range of omnivorous meals. The GWP of this version was 37% higher. This indicates that reducing the number of animal-based meals and optimising the objectives was effective in reducing the GWP, and that optimisation was as effective as a blanket policy. Some objectives may occasionally become slightly worse as the overall function is optimised, as a combination may be found which performs so well on one objective that the others are sacrificed.

Table three shows an example of a one-week plan allocated by the model to a group of people with a variety of dietary restrictions. Tables four and five show the order for the full 370-day period. The total mass of food to be delivered is well within the carrying capacities of the SDA and Dash-7 mentioned previously.

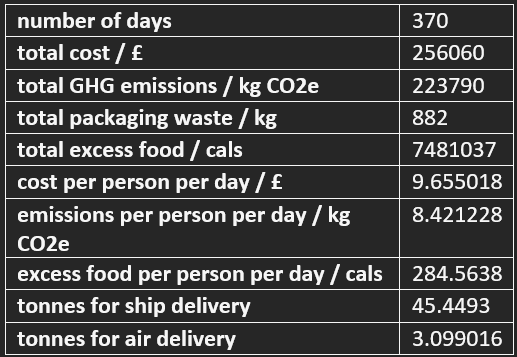
*Figures five and six – Solutions after solving for two minutes for different diets.*



*Table three – One week of a plan.*



*Table four – Yearly shopping list.*



*Table five – Summary of the order.*

Dickens (2021) estimated that food sent to Rothera on the SDA for 2020 contributed approximately 263,919 kg CO2e. This figure did not include deliveries by air, which have a higher transportation GWP. The output from the model suggests a plan for which it is estimated to be 221,370 kg CO2e including aircraft deliveries, a possible reduction of 42,549 kg, or 16%. The improved efficiency of the SDA compared to its predecessor does not contribute to this reduction because it was not considered in the shipping calculations due to a lack of data. The other objectives cannot be compared because there were no data available about them, although the model offered improvements compared to starting benchmarks on all objectives during its runtime.

# Conclusions and Suggestions

The output suggests a plan with a possible 16% reduction of GWP. The model satisfied all the practical and nutritional constraints. This indicates that AI could help BAS plan food purchasing strategies to optimise objectives. Other AI methods could be used to incorporate more randomness and adaptiveness into the search. Acquiring more data could open up more opportunities to use other methods. BAS can potentially improve the GWP of their food orders without implementing a blanket ban on red meats or other strict policies.

It may be beneficial for BAS to provide staff at Rothera with vitamin D supplements.

BAS could investigate the option of building cellars in permafrost to reduce the need for powered refrigeration.

BAS could consider providing guests with a future menu before they arrive, giving the operations team time to order the food in advance and reducing food waste, possibly with a note to diners explaining the environmental impacts of their choices. BAS could survey personnel to determine what dietary changes they would be willing to undertake.

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# Appendices

Links to work (GitHub, Trello) and personnel data

Shopping list

Menu

Test outputs

## Appendix A –

## Appendix B –