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  Artificial Intelligence for Environmental Risk

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Optimising remote field station supplies

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# Abstract

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# Introduction

The British Antarctic Survey (BAS) conduct research on a range of important scientific topics including climate change, biodiversity and the natural sciences. Field expeditions to Antarctica are necessary to facilitate much of this research.

BAS operations teams are responsible for providing all the resources required to sustain hundreds of people working at Antarctic research stations daily. The Rothera research station is the largest of these stations, regularly housing over a hundred people at once. Demanding work in remote, harsh conditions necessitates that these people are given the best possible diets, and there is no room for compromise or oversight when planning their nutritional intake. However, supplying the food is logistically challenging and has a considerable carbon footprint and financial cost.

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 research station amounts to around one percent of greenhouse gas (GHG) emissions associated with BAS’ operations, it is likely easier to change than other things such as shipping schedules, which are more tightly controlled and constrained.

This work uses carbon dioxide equivalent (CO2e) as the unit to express the global warming potential of GHG emissions associated with actions, decisions and objects. The terms ‘carbon footprint’ and ‘global warming potential’ (GWP) are also used to express the potential effect of choices on GHG emissions and their contribution to climate change. These terms are used by the UK government’s Department for Environment, Food and Rural Affairs (2014). CO2e values are often estimated based on averages, and not precisely measured, but are universally understood and food production data using this measurement were plentiful.

Modelling and optimisation of constraint-satisfaction problems is a topic of Artificial Intelligence (AI) in which combinations of parameters are chosen to search for optimal solutions to a given problem, measuring performance by a defined objective (Hooker, 2002).

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

# Background

## Rothera research station

Rothera houses a minimum of 22 people in the winter and up to 170 people in the summer, including a resident chef who prepares the meals for the group. Movements of people, aircraft and the Sir David Attenborough (SDA) ship are scheduled a year in advance and food orders are then made according to these plans. Food is brought in bulk on the SDA. Because the food needs to last a long time in storage, fresh food is considered a treat and is not usually part of the standard menu, although some fresh food 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 recycled or otherwise handled according to UK waste disposal practices.

The team at BAS advised that for this plan, meals would be offered as varied buffets, with a number of meal options from which people could choose, and optional side dishes for people who desire extra portions. Some members of staff stay at the station for 18 months. Due to their long stay in such a remote, bleak environment, their mental health is a serious concern when planning meals. It is essential for meals to be enjoyable and varied to help prevent boredom.

## Objectives

Although the aim of the project is expressed simply in human language, it is a multi-objective optimisation 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 and enjoyment of meals, and satisfying nutritional requirements, dietary restrictions and delivery schedules.

A satisfactory solution could be used to produce a meal plan for the coming year and its associated food order details along with measurements of objective performance. These suggestions could be used to help the operations team plan the meals and food purchasing strategy.

# Methodology

## Communication and organisation

Fortnightly meetings were held between the developer and the supervisor at BAS. A meeting with people from the BAS operations team was held near the start of the project to agree on the project criteria and required specifications. Minutes from these meetings are in appendices x to x. A backlog of tasks was constructed based on the requirements set out by the BAS operations team to guide the development and ensure that milestones were met. A Trello board was used for project management and task organisation, and code was held in a GitHub repository.

## Data and technology

A spreadsheet containing the previous year’s scheduled arrivals and departures of people and transit vehicles, as well as people’s job roles and genders, was provided by BAS. A copy of the spreadsheet, shown in appendix x, was then created with people’s personal information removed to protect their identities and to ensure the original data remained unchanged.

No data related to food purchasing or meal arrangements were available for the project. This meant that the developer had no knowledge of where food was purchased, how the logistics were planned, what system was used, whether there was a budget, how food orders were structured, what meals were typically offered, the costs or quantities of food items or how meals were planned. There was also no information available regarding people’s nutritional requirements, allergies or dietary restrictions. Due to the lack of data and knowledge, estimates were made for food purchasing calculations using a UK supermarket web site (Tesco, 2022) and assumptions were made about the structure and variety of meals. It was assumed that three different choices of breakfast, lunch and tea would be offered each day.

The project aims to satisfy the principles of Findable, Accessible, Interoperable and Reusable (FAIR) data, defined by Wilkinson et al. (2016). A copy of the personnel schedule data was included in the program files, but people's names were removed to comply with General Data Protection Regulations (Information Commissioner's Office, 2018). All other information sources used for the development of the program were also listed in the program files and are referenced in this report. Instructions on how to reproduce the results were given in the ReadMe file and are shown in appendix x.

MiniZinc was used as the constraint modelling language and Python was used for data pre-processing and post-processing. Both these languages are open-source. No specialist computing infrastructure is required to run the code other than a typical personal computer with an up-to-date operating system. Random dietary requirements were generated for the batches of MiniZinc data. These data files were included in the repository so that the results shown could be exactly reproduced.

## Dietary requirements

Required amounts of macronutrients for guests were estimated according to the NHS (2019) who state that exact amounts depend on age, gender, state of health, lifestyle, height and other genetic considerations. The NHS (2019) state that, typically, men require 25 percent more calories than the amount required by women, with an average daily calorie requirement given as 2000 for women and 2500 for men. The provided personnel data suggest that the majority of people at Rothera from 2021 to 2022 were male. All the personnel are adults of working age, so it was assumed that age would not be a significant consideration for calculating nutritional requirements. The cold temperature and physically demanding roles of personnel were important factors to consider. Boltz (2005) advised that people with the most physically demanding jobs, such as manual labourers, may require double the daily calories they would consume if they had a sedentary lifestyle. Other nutrients must also be scaled up along with calorie intake, 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, varied diet, because micronutrients are found in abundance in vegetables and other ingredients. The exception is vitamin D. The NHS (2020) advises that people who spend the majority of their time indoors, or 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 daily nutrition required by a healthy adult woman with a mildly active lifestyle. Men were identified from the data and their required amount of each macronutrient were increased by 25 percent. Job roles were assessed, using the role descriptions given by BAS (2015b) and categorised as sedentary, moderately active, with a 50 percent increase in nutritional requirements, or very active, with a 100 percent increase in nutritional requirements. These labels, shown in appendix x, considered the amount of physical work, such as lifting objects and walking, and the amount of time spent outdoors because of the harsh climate and weather. Anyone whose role included field work or diving was classed as very active even if their job role was typically more sedentary. This meant that the majority of personnel were classed as moderately or very active, and an average requirement of 3261 calories per person per day was estimated. Table one shows the nutritional requirements estimated by the program.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Calories | Carbohydrate / g | Fat / g | Fibre / g | Protein / g |
| Minimum baseline before adjustments | 2000 | 225 | 44 | 21 | 45 |
| Average requirement per person per day | 3261 | 367 | 72 | 34 | 73 |

*Table one - Average nutritional requirements before and after adjustments by the program.*

Because there was no information provided about people’s health or dietary restrictions, a function was created to generate random restrictions and allergies and append this information to the personnel data to be used with the model. Random numbers conforming to a Gaussian distribution assigned a number 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 found in the general British population, with approximately one percent of British 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 as well as common allergies and intolerances, and people with diabetes who need to control their sugar intake. Other considerations include religious diets, such as a provision for halal meats, but it was decided with the BAS operations team that since there would be a choice of three meals at each meal time, and a variety of meats and vegan foods would be offered, this would not likely become a problem. If later desired, meat categories such as red meat, white meat and fish could be introduced and included in the list of potentially refused ingredients. Alcohol was also not included in this list because alcoholic beverages are an occasional, optional treat and do not form part of the main meal plan. It was important to confirm that people with any combination of allergies or special diets could eat a balanced and varied diet. Table two shows an example of a daily meal plan and which options would be available to some people with dietary restrictions. 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 scenario and is a control measure. Person C can still eat a selection of foods. The addition of optional extra side dishes helped to ensure that all personnel could choose to eat as much food as they wish. If there are no people with a certain dietary restriction on a particular day, the model is not obligated to offer meals which satisfy that restriction.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Meat** | **Milk** | **Egg** | **Gluten** | **Nuts** | **Seeds** | **Added sugar** | **Person A vegan** | **Person B**  **coeliac** | **Person C**  **sensitive to all** |
| **breakfast** | fullEnglish | yes | no | yes | no | no | No | no | unsuitable | suitable | unsuitable |
| **breakfast** | veganPorridge | no | no | no | no | no | No | no | suitable | suitable | suitable |
| **breakfast** | Yoghurt | no | yes | no | no | no | No | no | unsuitable | suitable | unsuitable |
| **lunch** | mushroomSoup | no | no | no | no | no | No | no | suitable | suitable | suitable |
| **lunch** | pepperoniPizza | yes | yes | no | yes | no | No | no | unsuitable | unsuitable | unsuitable |
| **lunch** | vegChowMein | no | no | no | no | no | No | no | suitable | suitable | suitable |
| **lunch side** | bakedPotato | no | no | no | no | no | No | no | suitable | suitable | suitable |
| **lunch side** | roastPotatoes | no | no | no | no | no | No | no | suitable | suitable | suitable |
| **dessert** | berryCrumble | no | yes | no | yes | no | No | yes | unsuitable | unsuitable | unsuitable |
| **tea** | mushroomSoup | no | no | no | no | no | No | no | suitable | suitable | suitable |
| **tea** | pepperoniPizza | yes | yes | no | yes | no | No | no | unsuitable | unsuitable | unsuitable |
| **tea** | vegChowMein | no | no | no | no | no | No | no | suitable | suitable | suitable |
| **tea side** | bakedPotato | no | no | no | no | no | No | no | suitable | suitable | suitable |
| **tea side** | roastPotatoes | no | no | no | no | no | No | no | suitable | suitable | suitable |
| **dessert** | berryCrumble | no | yes | no | yes | no | No | yes | unsuitable | unsuitable | unsuitable |

*Table two - Example of a typical daily buffet and its consequences for dietary restrictions.*

An anticipated problem with the buffet arrangement was that all the servings of a particular meal might be taken by other people at the front of the queue, leaving only options which are unsuitable for those at the back of the queue who may have allergies. This problem is not specific to this project and could potentially occur at any buffet type of meal. One option would be to prepare more servings than necessary to create a surplus, but this could lead to increased food waste. Another option would be to provide each person with a set meal and no choice, but this would be restrictive and unpleasant for the diners. A less extreme option would be to provide personnel with a menu so that they could select their desired meal and the chef would know how many servings to prepare for the group. Doing this daily would introduce the risk of running out of certain ingredients, as exact amounts could not be ordered a year in advance. This problem could be tackled by providing guests with a future menu and asking for their meal selections in advance of their visit, giving the operations team time to order the food and reducing food waste.

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

The meal plan includes breakfast, main meals, side dishes, desserts and occasional treats. The 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 still be included in the order details. The examples shown in the results have a set frequency for treats as once per week.

Although a vegan or flexitarian diet is often associated with a reduced carbon footprint, and research by Röös and Rysselberge (2021) supports this, the consultation with the BAS staff revealed that some personnel would be unwilling to adopt a vegan diet and requested a variety of meat options. The program aimed to offer at least three meat types per week, such as fish, beef, pork, lamb or poultry.

## Transport

The majority of food is brought to Rothera from the UK yearly in bulk on the SDA. BAS also use Twin Otter and Dash-7 aircraft for smaller, more frequent deliveries of equipment, passengers and fresh food, from South America and the Falkland Islands (BAS, 2021a). The personnel data show that all the scheduled flights to Rothera in the period were performed by the Dash-7, and that there was no scheduled transit by any vehicles in the Antarctic winter, which was the period from May to September. Because of this, the program does not allow any fresh foods to be included in the menu during the winter season.

To estimate the GHG emissions and financial costs associated with transport of foods, assumptions were made in the absence of specific data. For the SDA, the total potential capacity for food was assumed to be the total cargo capacity minus the fuel storage capacity, given by BAS (2021b). The voyage was assumed to take 20 days on average from the UK to Rothera sometimes via the Falklands. The emissions and fuel consumption were taken from average cargo ship consumption from Tiseo (2021) but this is probably not very accurate because the SDA is a multi-purpose vessel and not a cargo ship. It was assumed that UK fuel prices would apply to the SDA. The cost and emissions of moving 100 g portions of food were then 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 would be directly from the Falklands to Rothera, non-stop. This distance would mean that the aircraft could not travel fully loaded, but the maximum loading capacity was taken from Frawley (1995). The average number of passengers per flight was calculated from the change in the number of people at Rothera coinciding with scheduled flights in each direction and was found to be 4.26 people including one pilot. The average mass of 4.26 British men in heavy winter attire was subtracted from the carrying capacity, along with the required extra fuel for the return journey and safety surplus. The emissions and fuel consumption were taken from Campbell (2022) and the cost of aviation fuel in the UK was applied.

Realistically, it is obvious that neither the SDA nor the Dash-7 would ever travel with their entire cargo capacity full of food, but this was theoretically assumed for the estimates so that a fair and proportional comparison could be made between the two vehicles. Both journeys were considered one-way for simplicity because the vehicles may have taken detours via other research stations before returning, and would also return with waste, equipment and passengers.

Similar estimates were also made for the Twin Otter aircraft. These assumptions and estimates are shown in more detail in appendix x.

## Practical considerations and assumptions

It was not known where BAS purchased food, or whether food was purchased from the UK or South America, so Tesco (2022) was used to get comparative costs, quantities, packaging information and nutritional values of ingredients. It is likely that BAS would buy ingredients in bulk and the cost and packaging waste would be less.

Most food at Rothera is dried and tinned, and some is frozen. Values assigned to frozen foods were based on running costs and emissions per unit of space for household freezers in the UK, for 100 g portions of ingredients stored. It was assumed that non-refrigerated ingredients would be kept in a heated building due to the cold temperatures outside, to prevent them from freezing and possibly losing their structure or texture. Barreneche et al. (2015) showed that the energy required for cooling is typically more than the energy required for heating per unit of space, and the ambient temperate has little effect on the energy cost of cooling, but larger spaces are usually heated so the overall energy requirement is usually higher for heating. Energy costs were taken from the cost of electricity in the UK, which is probably not accurate for Rothera, which uses a combination of petrol generators and solar panels. Despite the lack of accuracy from these assumptions, it should still be possible to draw relative comparisons between different options. People in the Arctic have stored frozen food for up to a year at a time in cellars dug into permafrost which have been able to maintain low enough temperatures even during the summer (Brown et al., 2017). This method requires no electricity or fuel and therefore has a smaller financial cost and carbon footprint than using electric refrigeration. BAS currently store some food in freezers, according to Dickens (2021). Although summertime temperatures at Rothera can stay higher than ice melting point for several weeks at a time, there is permafrost (Baio et al., 2014).

Cooking costs and emissions were calculated based on the time required to cook meals, whether they would be cooked by oven, hob or microwave, and the number of portions that would be cooked at once. As explained by Janestad et al. (2003) the energy required for oven cooking does not increase linearly with cooking time as with hob and microwave cooking 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 in the model, but the financial cost was more relevant.

Packaging waste could be viewed from the perspective of comparing the environmental effects of disposal methods such as recycling, landfill, incineration and the risk of waste travelling into the oceans, or it could be viewed from the logistic perspective of the cost and emissions of transporting it to disposal centres. It was assumed that packaging waste would be returned on the SDA on its return journey after the bulk food delivery, and because this would leave the SDA with a large available storage capacity, it was decided that it would be more useful to consider packaging waste from the perspective of disposal methods. The focus was on non-recyclable packaging, which is mainly found as soft plastics and mixed materials. Non-recyclable packaging with and without their contents were weighed and average masses of non-recyclable packaging were estimated for different ingredients per kilogram of ingredient. Show this in appendix. Additionally, it was assumed that some recyclable packaging would end up in landfill or become lost (Greenpeace, 2021) so a smaller penalty was included for recyclable, non-biodegradable packaging.

## Constraint modelling

When modelling the constraints of the program, the aim was to capture the key conditions usually communicated by human language and embed the intelligence and 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 which could tolerate some degree of compromise, such as the GWP of the food order, were encoded in the objective function as soft constraints. Solutions may only be valid if they satisfy all the hard constraints. A satisfactory solution is a valid solution which offers a reasonable optimisation of the objective function. For a problem of this size and complexity, the goal, but not the expectation, is to find the globally optimal solution; we wish to find the best possible solution but the search space is too large to realistically expect to find it exhaustively (Dechter, 2003).

Initially, the model was developed on a hypothetical week of data for 25 fictional people. The meal options and number of portions of each option served were chosen for each mealtime of each day in that week. When the real data were added, it became computationally costly for different daily meal 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. The model then repeated that weekly menu throughout the period of data, adjusting the number of servings of each meal according to the personnel data daily.

Breakfasts and main meals were considered essential and they contained the largest quantities of food so to ensure adequate nutrition and reduce food waste, the total number of servings of these at mealtimes was constrained to be exactly 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 some extent, to give the model some freedom to find different solutions. The upper limit of desserts and treats was still fixed as the number of people present, but it was double this value for side dishes because it is reasonable to assume that some people want more than one side dish.

Without constraints to introduce variety, the solver found one or two recipes and repeated them for the menu. Constraints were set so that each meal option at the same mealtime must be different and different meals must be offered throughout the week. For breakfast and main meals, constraints were set to ensure that everyone with allergies or dietary restrictions could eat something and that there were enough servings of suitable foods for those people.

Because the occasional 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 also constrained to prevent the same treats occurring twice in a row. Occasional treats were not included in the daily nutrition plan because their purpose was for mental, not physical, health.

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

A minimum number of servings of each meal option was set because otherwise the model tended to choose to offer many portions of one meal option at the buffet, and few or no servings of the other meal options at the buffet. The minimum was defined as a proportion of the number of people present.

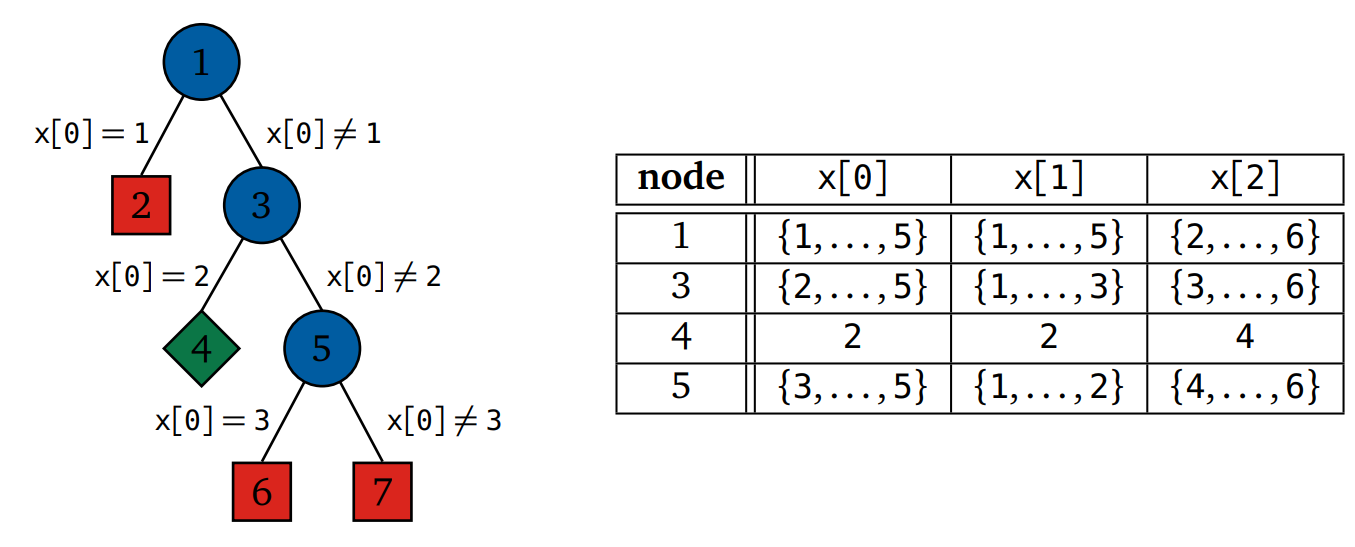
Finally, constraints ensured that the personnel were provided with enough of each of the nutrients every day, as a minimum.

Introducing and tightening hard constraints reduced the number of valid solutions, making the optimisation process faster but restricted to solutions which generally performed worse on the objectives. A considerable amount of development time was spent seeking a balance between solving time, objective performance and a reasonable variety of meals. 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 laptop implied a limit to the computational complexity in order to receive solutions. To achieve more realistic solutions, the variety of meals was implemented as both a hard and a soft constraint. This is an example of why humans must monitor and evaluate decisions made by AI models before implementing them in the real world (Chen et al., 2021).

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

## Solving technique

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



*Figure one – A 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 as the solver for this project due to its overall success and because it is quick and easy to implement in MiniZinc, enabling the human requirements of the application to be prioritised for development. If more time was available on this project, it could be useful to investigate other solving libraries, create a custom search engine using Gecode, or create a search algorithm from scratch designed especially for this specific problem. The default technique employed by Geocode was based on an exhaustive traversal through the entire search tree and therefore tended to begin at certain positions of each data structure, leading to repetitive and similar results, and taking too long to find other, more varied solutions. Other areas of AI could be used to incorporate more randomness and adaptation into the search, such as reinforcement learning to trial randomised routes through the tree, or an evolutionary algorithm to combine and 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, some with several nested loops, attempting to solve the problem with the entire 370 days of data resulted in no improvement of the solution over time, when running for at least three hours, and was also prone to memory overflows. the data were split into smaller batches of dates and the model processed each batch consecutively. The maximum size of each batch was determined by iterating over dates in the whole schedule and adding the numbers of people on each day. Once this matrix of people and days exceeded 3000 people, the data to this point were saved into a MiniZinc data file. Figure two shows the tests to determine the ideal batch size. All tests with data matrix sizes larger than 4000 elements failed to find a solution within 20 minutes. The plot indicates that the model was able to produce consistent results with a variety of data, except where the data were so small that not a full week’s menu was constructed.

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

## Objective function

Several different expressions of the objective were tested, attempting to minimise one or a combination of financial cost, associated emissions, excess food, packaging waste and the lack of variety of meals, which was measured by summing the difference between the number of servings of each option at mealtimes so that a larger number represented fewer options for the majority of people. Potential food waste was measured as the excess calories and other nutrients above the minimum requirements of the group, with the minimum amount set as a hard constraint. Figure three shows the different ways in which the objective function could be encoded and weighted. All the outcomes are similar when values of objectives are scaled to a similar magnitude, which suggests a possible lack of variety of solutions available 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 one objective which had little overall effect on the sum of all objectives.

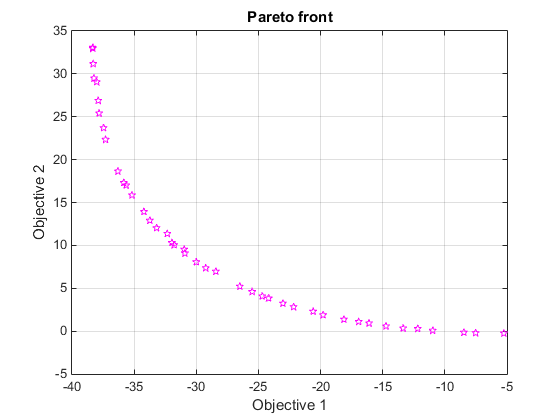
*Figure three – Comparison of performance using different objectives.*

Floating-point numbers could not form part of the objective function 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, division or multiplication. A benefit of this was the relatively small memory space requirement during runtime. Because of this, some values were later scaled up or down 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 then multiply them instead of summing them. This would allow the developer to start with an unbiased objective, with the opportunity to include deliberate and specific weights to variables. Summing and not normalising the variables in the objective function 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 in similar magnitudes.

Finally, the objective function chosen to be minimised was the total 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, sometimes with one or two more improvements over the next ten minutes. Timings, benchmarks and more objective tests can be viewed in appendices x to x.

# Results & discussion

Figure four shows a pareto front of solutions which perform equally on a function of two inversely related objectives. This project is more complex because it contains five objectives, although most of them are not inversely related; variety is inversely related to the other objectives. Having too many objectives, particularly inversely related ones, can reduce performance because the extent of optimisation of each variable may be sacrificed to produce a solution near the middle of the pareto front, or one objective may dominate the others, to find a position at one end of the pareto front.



*Figure four – Example of a pareto front for two objectives from MATLAB (2016).*

Figure five shows a comparison of implementing different diet types for the buffet. There is a focus on 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 nutrition 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 is a very small reduction in associated emissions as animal products are phased out, which is possibly not larger because most of the meals which the model chose in the meat containing versions were still vegetable-based anyway to satisfy dietary restrictions, maintain variety and minimise GWP. There was a slight reduction in cost and emissions in winter plans, when aircraft could not reach Rothera, but it was not considered useful to discuss this in more detail because flight schedules are unlikely to be adjustable based on this. Furthermore, there is a risk of bad weather delaying aircraft arrivals, so the menu is not reliant on aircraft deliveries. All essential meals are made from bulk ingredients.

*Figure five – Values of objectives from solutions after solving for two minutes for different diets.*

Final output menu

Final output shopping list

Dickens (2021) estimated that food sent to Rothera on the SDA for the year of 2020, containing 366 days, contributed approximately 263,919 kg CO2e. This figure did not include foods delivered by air, which have a higher transportation GWP. The output from the model suggests a plan for which it is estimated to be approximately 221,370 kg CO2e, a possible reduction of 42,549 kg. The improved efficiency of the SDA compared to its predecessor does not contribute to this reduction because this was not taken into account in the shipping calculations due a lack of real-life data. This figure also contains some foods delivered by air, so would likely be lower if these were discounted.

# Conclusions

# Suggestions for further work

What can BAS do to improve the situation

Which objectives can be best improved

How to improve all objectives

Can all objectives be improved at once

Vitamin D

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

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

providing guests with a future menu before they arrive, giving the operations team time to order the food in advance and reducing food waste.

Ruminent meat

Survey people to find out what diets they would be willing to adopt

Take bits of that ^ for conclusion

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# Appendices

Links to work (GitHub, Trello) and personnel data

Shopping list

Menu

Test outputs

## Appendix A –

## Appendix B –