

**Optimising animal diets at the Johannesburg zoo**

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# Abstract

The feeding of all captive animals is more complex than merely combining compatible feed ingredients and rationing the amounts to what is believed to be adequate. The roles of a modern zoo are to conserve species from extinction, educate the public on conservation, to serve as an institution for research and provide entertainment for the public. The keystone of these four roles of a zoo is the welfare of animals. Therefore appropriate animal diets must be presented to the animals. This project, titled; Optimising Animal Diets at the Johannesburg Zoo is conducted with the aim to reduce the expense that the zoo is experiencing. The Johannesburg Zoo is home to 2040 animals of which there are 380 different species that all need to be fed on a daily basis. The important aspects which are addressed in this project is firstly determining the animal diets at least possible cost and secondly ensuring that all the diets are as nutritionally balanced as is allowed for given the feed ingredients. A model, capable of determining least cost diets is developed in this project. The model is applied to the 80% of the feed ingredients that contribute primarily to the high expense of feeding animals. Along with the model, an interface is constructed on which the nutritionist is able to change the values that have an effect on the model. Aspects such as nutrient compositions of feed ingredients and each animal's specific dietary need play an important role when considering determining least cost diets. The Johannesburg Zoo is desperately in need of reducing their expenses. The goal of this project is to assist the zoo in reducing their expenses by determining least cost diets which also incorporates the nutrient composition requirements that will benefit the animals.

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# List of Acronyms

**BMR** Body Mass Ratio

**Jhb** Johannesburg

**LP** Linear Programming

**OR** Operations Research

**UM** Ultramix

**ZSL** Zoological Society of London

# Chapter 1

## Problem Overview

### 1.1 Introduction

Man has kept animals in captivity since the very beginning of civilization, animal remains were found in tombs showing that the Egyptians had kept animals captive dating back to 2000 B.C. More animal collections were found at around 1000 B.C. in China, during the Chou Dynasty.

In 1826 Sir Stamford Raffles founded the Zoological Society of London (ZSL). This was charity devoted to conservation and education. The ZSL opened London Zoo in 1828, which was to be the world's first scientific zoo. There are thousands of zoos in the world, where South Africa in particular is home to 23 zoos. The role of these zoos is primarily for conservation of endangered species. Other roles include education, research, entertainment and training.

This project specifically focuses on the Johannesburg (Jhb) Zoo in South Africa. The Joburg zoo has served citizens for more than 100 years. Herman Eckstein donated the land in Saxonworld in 1904, with a small animal collection donated by Sir Percy Fitzpatrick. Over time the nature and operation of the zoo has changed dramatically. Currently the zoo houses 2050 animals with 380 different species. The Zoo has the following mission:

“To successfully develop and manage the Joburg Zoo as a world-class African Zoo driven by competent, motivated and customer-focused people.”

All successful businesses take the cost of expenses seriously and minimize the costs as far as possible. In order to achieve their mission in being a world class zoo the costs of running a zoo must be taken into consideration. Zoos in first world countries has the advantage over South Africa in that the target market, the public, in those countries have a higher level of disposable income. The zoos are thus able to generate more income both in the form of gate takings and other revenue generating operations within the zoo. In addition, other cultures make a visit to the zoo a more frequent family outing compared to the South African public. Jhb is subsidized by the government; the subsidy has been decreasing since 2002. Further more the zoo generates income through sponsors, gate

takings and entertainment projects launched at the zoo. A special event such as the Spar Zoo run is held monthly to generate more money. However, looking at the zoos profit margin and the amount of money budgeted for improvement, it is clear that there is not enough money for the zoo to succeed in developing and managing the Joburg zoo as a world class zoo.

## 1.2 Problem definition

Feeding the animals at the Joburg Zoo costs on average R300 000 per month, second only to employment costs.

Diets are roughly worked out according to the requirements of the animals and the costs of feeding the animals are rarely taken into consideration. The problem is evident: feeding the animals is very expensive and an opportunity of minimizing cost is at hand.

## 1.3 Project Aim

The aim of the project is to determine least cost diets for animals while meeting their nutritional requirements. Further more the model will be linked through an excel interface through which the nutritionist is able to change values such as costs of food, animal weights, the number of animals that must be fed and each animals BMR value when ever an animals physical condition changes. When the model is run, the results are exported to another spreadsheet. The nutritionist is able to further rework the information into diet sheets. The diet sheets are then handed to the animal keepers who feed the animals.

## 1.4 Project Scope

The animals will be grouped into carnivores, omnivores, antelope and pachyderms. The project focuses on all animals that consume any form of meat or grass as these feed ingredients contribute primarily to the large cost of feeding the animals at the Johannesburg Zoo. Figure 1.1 illustrates the costs associated with these specific feed ingredients compared to the cost of vegetables and produce or fruit.

Each group of animals has different nutritional requirements and compatible feed ingredients. An illustration of the carnivore and omnivores groups showing the relationship among the broader categories of animals as well as the smaller defined groups within the categories is available in Appendix A.3. The antelope and pachyderms are all grouped together and have no defined groups within. They all forage from the same feed ingredients namely; lucerne, teff, boskos and antelope pellets.

To accommodate different diets for male and females the nutritionist should be able to enter the animals weight into the excel interface. The corresponding energy requirement is calculated and the diet is worked out according to that specific energy requirement. The scope of animals covered by making weight the determining factor of energy broadens the

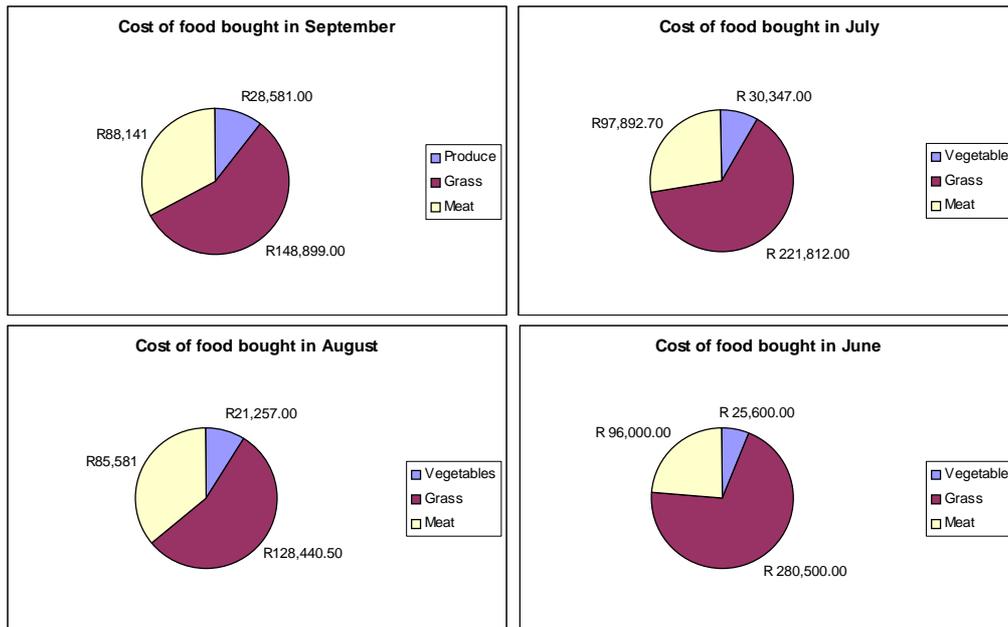


Figure 1.1: Comparison of costs between grass, meat and produce or vegetables

range of animal diets that are covered. Energy requirements can be calculated for any adult, sub adult or juvenile animal.

Diets for ill or very old animals are excluded as their dietary needs depend on their specific illness. Elderly animals get problems with their gums or teeth, and special diets are fed to accommodate those kinds of problems.

## 1.5 Optimal nutrition

Zoo nutrition evolved in the late 1970's and has become a full-time job worldwide. Designing diets for animals is not as trivial as it may sound because different feeding strategies exist and there are specific dietary needs for a large variety of animals.

Animals in captivity do not get the proper exercise as they would in the wild; therefore feeding animals the right food is essential in determining their health, size and state of well being.

Zoo nutrition is unique to each zoo and is based on several requirements determined by the specific zoo. At the Joburg zoo the nutritionist strives to feed animals according to the amount of kilojoules that are needed to give an animal a healthy life. The effects on energy intake are explained in Section 1.5.1.

The nutritionist at the Joburg Zoo, Lorna Fuller, has the job of working out nutritionally balanced diets for every animal. A diet is considered to be nutritional balanced if it adheres to the following three criteria:

**Natural** A diet should provide appropriate levels of known essential nutrients. Preparing the diet as close as possible to what the animal would eat in the wild is a goal

for animal nutritionists. A nutritionally balanced diet provides the animal with the right amounts of all the known nutrients required.

**Consistent** Ensures that the required nutrients are consumed by the animals. A poor palatability or inappropriate form and presentation can lead to a loss of food and money. It is of no value if the animal only eats certain foods and therefore it is important to monitor the diet intake periodically to ensure that the majority of foods are consumed.

**Realistic** A practical diet is one which can be prepared by the appointed person using ingredients which are readily available to the zoo. A diet which falls within the budgeted guidelines and meet the nutritional requirements is a practical and economical diet, therefore making the diet realistic.

Obtaining nutritional least cost diets does not mean feeding the animals less food, but feeding them the right food in the most economical way. The required energy intake is the main requirement and constraint on which the model is based. However, nutritional requirements such as the levels of protein, fibre and fat will also be included to ensure even better diets nutritionally wise. The nutrient requirements will only be incorporated into the model if the energy constraint allows for it.

### 1.5.1 Energy in an animals' diet

When animals have an excess intake of energy, their body will gain weight resulting in heart and other related diseases. Continuous negative energy balance would lead to illness and malnutrition.

Nutrients are classified in two broad categories: macro- and micro- nutrients. Macro-nutrients are those that are needed by the animals' body in large quantities. The three macro- nutrients are: carbohydrates, proteins and fat. Micro-nutrients are needed in much smaller quantities and include vitamins and mineral elements.

Carbohydrates are the main source of energy and have no other identified uses. Proteins on the other hand could be used as a source of energy but only ten percent of protein intake contributes to energy. The remaining ninety percent is used for bodily functions and development.

Fats are basically used for energy; apart from the insulation they give the body when stored in the adipose tissue. A deficiency in fat intake has no known effect but a small quantity omega-3 fatty acid within fats are known to be good for health.

Different macro and micro nutrients are important in carnivores, herbivores and omnivores. In the group carnivores and omnivores, protein and fat are the important nutrients that are of interest. The requirements that must be met in herbivores (antelope and pachyderms) are: protein and fibre. The omnivores diets are only worked out according to the amount of meat they require as the vegetables and fruit comprise of less than 20%

of their diet. The meat in all the omnivore diets is worked out at 80% of their total energy requirement. Energy and nutrient requirements are explained in Section 2.6.

## **1.6 Research Design**

The main purpose of this project is to develop a model that is capable to determine least cost diets for animals while meeting certain nutritional requirements. Thorough research is conducted in Chapter 2 with the intention to discover possible techniques to solve the problem.

The model will include all animals that feed off some form of grass or meat. Grass includes: lucerne, teff, boskos and antelope.

Meat includes: beef carcass, chicken, chicks, beef heart mince, cat food, horsemeat, rabbit, fish (hake, sardine and banker).

## **1.7 Research Methodology**

It is imperative to learn all about the animal diets and their foraging requirements before attempting to determine least cost diets for animals. Each animal's dietary needs and requirements must be known as well as the specific requirements and limitations that are applicable to the Jhb zoo.

There are many different feeding strategies that nutritionists use. The strategy greatly depends on the knowledge of the nutritionist, the environment and economic impact the strategy may have. In the case of the Jhb Zoo there is no set strategy. The nutritionist is feeding the animals based on what she has found through trial and error in the past 25 years. Although she clearly has tremendous knowledge on how the animals should be fed, she cannot formulate diets that incorporate all the requirements.

Research is done on possible techniques which can be used in achieving the aim of determining least cost diets. Extensive research is also required to obtain the latest dietary requirements and nutrient compositions of feed ingredients.

Literature on nutrition is also available in Section 2.6. The goal is to familiarize terms and calculations which is used and referred to throughout the rest of the document.

## **1.8 Structure of document**

Chapter 2 reviews existing approaches on possible ways in which diets can be formulated while minimizing the costs using a Linear Programming (LP) approach. After the literature review the problem is formulated in Chapter 3. The model is then executed, results are analyzed and discussed in Chapter 4. Chapter 5 includes the recommendations, possible future aspects which may be addressed and the conclusion.

## Chapter 2

# Literature Review

### 2.1 Operations Research

Operations Research (OR) is typically concerned with optimizing either the maximum (profit, assembly line performance, crop yield, bandwidth, etc) or minimizing (loss, risk, costs etc.) of some objective function.

OR originated during the Second World War, when the allied world sought the assistance of the scientific community to resolve certain operational problems. After World War II, the United States carried on applying OR in military applications and was sponsored by establishments such as the RAND corporation in California and the office of the Naval research in Washington D.C.

OR in industry developed in Europe when they suffered great loss after the war and was in need of industrialization. Since then OR gained acceptance in various disciplines, particularly engineering.

### 2.2 Linear Programming

Solving LP problems was discovered by Dantzig in 1947 with the help of J. Von Neuman. The basic assumptions that are made in accordance to linear programming are:

1. the linearity
2. non-negativity of variables

LP is one of the most widely used type of mathematical programming techniques. Some LP uses are identified: Fabozi (1978) wrote on the use of LP in capital budgeting. J.R. (1985) is one of the users in aggregate production planning. H. and R.P. (1975) exemplify the use in assignment problems and urban planning. Garkel (1986) also illustrated the use in scheduling.

Literature on LP are found with no difficulty. It is a popular technique that is used extensively throughout the world. More LP problems associated with the diet problem are explained in detailed in Section 2.4

## 2.3 History on the Diet Problem

The diet problem is one of the first optimisation problems which were studied back in the 1930's and 40's. One of the early researchers to study this problem was George Stigler. He made an educated guess of the optimal solution to LP using a heuristic method. In 1947, Jack Laderman of the Mathematical Tables Project of the National Bureau of Standards undertook solving Stigler's model with the new simplex method. He made it possible to solve the problem without relying on heuristic methods.

## 2.4 Associated Diet Problems

The literature that follows indicates all the possibilities of linear programming problems which can be incorporated into the final model. These associated problems are explained and some will be used together in formulating the complete diet problem in Chapter 3.

### 2.4.1 Blending Problems

LP is used to solve feed mixing problems. Katzman (1956) explains how this is usually done by trial and error methods taking into consideration the prices and different feed ingredients. This method is relatively easy but becomes a tedious process when there are many options of formulating a specific product or diet in this case. LP provides an exact and unique solution to the problem and is computed in a much shorter time once the model exists. According to the pioneer of animal nutrition F. V. Waugh the economic problem confronting the feed manufacturer is essentially a blending LP problem. The amounts of nutrients in the feed mixture are linear functions and the nutritionist wants to adjust his or her purchase of each feed ingredient in such a way that the mixture will provide at least a minimum amount of each important nutrient.

Munford (1996) illustrates a blending problem using LP by making use of a graphical manner shown in Figure 2.1. Let us assume that the protein requirement in a lion's diet consisting of beef and chicken must be met and that this requirement must be obtained as cheaply as possible. The protein requirement in 100 pounds of beef and the amount of chicken must be greater than or equal to 20 pounds.

Beef contains 69 % protein and Chicken contains 34 % protein.

$$0.69\text{Beef} + 0.34\text{Chicken} \geq 20$$

There are two more restrictions:

$$\text{Beef} \leq 5\text{£} \quad \text{(technical constraint)}$$

$$\text{Chicken} \geq 51\text{£} \quad \text{(legal constraint)}$$

To include the cost side of this problem, each pound of beef costs R 0.44 and R 0.32 for chicken. The food cost function is:

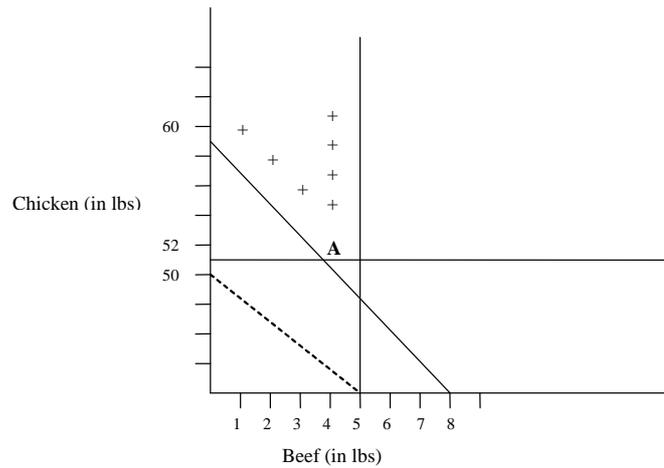


Figure 2.1: A Blending Problem using Linear Programming

$$F = 0.44 \text{ Beef} + 0.32 \text{ Chicken}$$

Any point on or in the "+" region indicates a feasible solution. Any point on a particular cost function line indicates the cost of a combination for Beef and Chicken. The slope of the line is determined by the relative prices of the two food types and is shown as the dashed line on the graph. Point A is the cheapest combination of Beef and Chicken that meets the requirements. This combination is 3.85 £. of Beef and 51.00 £ of Chicken. This simple problem can be solved very easily by trial-and-error method, or graphically. However, when there are several requirements to satisfy and many feed ingredients to choose from, a systematic computing technique for finding the minimum cost solution will be more practical.

### 2.4.2 The Batch Mix Problem

Munford (1996) refers to batch mix problems as the maximum and minimum boundaries set for nutrient levels of diets. It is important to feed an animal at least  $x$  amount of a certain ingredient, but too much can result in illness or obesity. Feed compounding companies have used the batch mix methodology for years and they make use of LP to solve the problem.

Example: a seal can eat up to 5kg of fish every day but has a minimum intake of 3kg each day. This constraint is regulated as follow: Assume:  $c$  = the amount (in kg) of fish a seal eats every day. Therefore

$$3 \leq c \leq 5 \quad \text{(fish constraint)}$$

### 2.4.3 Multiperiod Decision Problems

Feeding demand changes in a zoo environment as animals are relocated, transferred to other zoos for reproduction, die or sold. To cover the problem of demand variation, the multiple period inventory decision models exists to address this problem. The Zoo must determine when to buy what ingredients. Prices on food and the demand for food can be forecasted. By minimizing the cost and including relevant constraints the optimal procurement of food and quantity is achieved.

An example obtained from Winston and Venkataramanan (2003): This part will be addressed in the form of constraints. Let:

- $d_{ti} \triangleq$  demand of food type  $t$  in period  $i$  where  $t = \{1 \dots m\}$  and  $i = \{1 \dots n\}$
- $x_{ti} \triangleq$  number of food type  $t$  to purchase in period  $i$
- $y_{ti} \triangleq$  number of food type  $t$  on hand at the end of period  $i$
- $c_{ti} \triangleq$  the cost of food type  $t$  in period  $i$

It is assumed that there are no penalty costs for storing food. Let:

$$\text{Total cost} = \min z \sum_{i=1}^n c_{ti}x_{ti} \tag{2.1}$$

subject to

$$y_{ti} = y_{ti-1} + x_{ti} - d_{ti} \tag{2.2}$$

$$y_{ti-1} + x_{ti} \geq d_{ti} \tag{2.3}$$

$$y_{ti} \geq 0 \tag{2.4}$$

$$x_{ti} \geq 0 \tag{2.5}$$

## 2.5 Available software models

There is a broad choice of feed formulation software packages in the market. The software range from simple, spreadsheet-based solutions to sophisticated and complex packages designed for large feed manufacturers that require multi-site, multi-server, and multi-blending capabilities. New and innovative add-on applications are being developed and introduced into the market every year. The software packages may also provide modules for inventory control, production, and interfaces to accounting systems among other features. Some feed formulation software is specifically designed for a certain species and they may provide tables of nutrient requirements or models of growth for those specific animals.

The following two models determine least cost diets. These software packages are

popular in the livestock farming industry.

1. BESTMIX Feed formulation and optimisation

BESTMIX Feed is an advanced least-cost feed formulation and optimisation package. The package has been known for years throughout the world for its extremely powerful functions: multiblend, ingredient allocation and bulk blending. The strength of this software has been combined with a highly practical and extremely user-friendly user interface. The disadvantages are that extensive training is required and the software is applicable to one species.

2. The Ultramix modelling system

The Ultramix (UM) is a flexible least cost feed formulation and modeling software package. It has been used in the UK and various countries for the past 10 years. In the UM the user describes nutrient requirements in terms of animal characteristics or other parameters using equations, just as one would in a spreadsheet. The numerical values produced by these equations are used to produce least cost rations and the results of which can be used by the modeler to compute subsequent rations. UM solves problems for formulating batch mixes with nutrient variability. This package is also only applicable to a single animal and is usually used in livestock farms.

## 2.6 Nutrition in the past

J.L and E.D. (1966) uses integer programming to plan institutional menus for a weekly and monthly period. Menu planning models also contain constraints that include the problem of tastiness and variety requirements.

M. et al. (1983) points to goal programming as a way to include more than one objective. The objective functions are maximizing nutritional requirements and obtain diets at minimum cost.

Brody (1945) derived the value for basal metabolism:

$$\text{kcal per day} = 70.5kgBW^{0.734}$$

Kleiber (1961) stated that the mean standard metabolic rate of animals is  $70 \times BW^{0.75}$  kcal per day. By computing the energy requirement with a standard equation and entering the weight of an animal into the excel interface, the complexity of distinguishing between different sized animals as well as females/males and growing and lactating animals are dealt with.

Animals' physical condition changes over time just like humans loose and gain weight. Besides the weight that change, the condition of the animal has to be taken into consideration. A Body Mass Ratio (BMR) indicates in what physical condition the animals' body is. Whether the animal's weight is normal, underweight, overweight or whether the

animal is growing or lactating, this factor is adjusted to calculate the actual energy needed for an animal. The factor is multiplied by the animals weighted energy requirement to determine the final energy required.  $BMR * 70 * BW^{0.75}$  The associated BMR values and animal conditions are shown below.

Table 2.1: BMR factors

BMR	Condition
1	Normal
1.5	Normal
2	Underweight
3	Growing
4	Lactating

The following table of data is based on the carnivore group and explains the nutrients and energy intake in a more understandable manner.

Any carnivores energy(kcal) requirement can be determined by:

$$\text{Energy} = 70 * \text{body mass}^{0.75}$$

Table 2.2: Food for carnivores and related cost per kilogram

Beef	Chicken	Chicks	Mice	Cat Food
R11.40	R21.00	R8.00	R100.00	R30.00

The required nutrients for a carnivore and the energy associated with each nutrient is given in Table 2.3. The % nutrient refers to the percentage of that specific nutrient available in one kilogram of food type  $i$ .

Table 2.3: Nutritional Contents

Food type	Beef	Chicken	Chicks	Mice	Cat Food
Protein%	22	18	17	17	33
Fat%	17	13	16	12	22
Vit A IU/g	0	1.08	9.11	10.6	15.3
Energy Kcal/g	2.91	1.99	1.48	1.88	4.48

Any carnivore's diet must comprise of at least:

$$\text{Protein} \geq 26\% \tag{2.6}$$

$$\text{Fat} \leq 16\% \tag{2.7}$$

$$\text{Energy} \geq \text{the computed energy} \leq \text{the computed energy} \tag{2.8}$$

Equation (2.6) and (2.7) are the nutrient requirements in all carnivores and omnivore diets. The nutrient requirements that are of interest in the antelope and pachyderm groups is

the percentage of fibre and protein included in their diets.

## **2.7 Solving method for the Diet Problem**

Both software packages have the limiting factor of only retrieving a single diet in an instance of running the model. These models are usually used in farms such as fish farms or any livestock farm where there is only animal species to consider. It can be used in the case of a zoo but the process of retrieving diets for all the animals will be time consuming.

It is clear from the above literature that a solution to the blending part of the problem, batching and multiperiod part can be solved through making use of LP.

LP is the traditional diet problem solving approach and will still be used in solving the problem at the Joburg Zoo. LP is used because of its simplicity, the availability of software Lingo and because the constraints and other requirements are treated as linear functions. This makes LP an adequate tool for solving the problem at the Joburg zoo.

## Chapter 3

# Feed Formulation

According to Rossi (2007) least-cost feed formulation is combining many feed ingredients in a certain proportion to provide the target animal with a balanced nutritional feed at the least possible cost. Although the formulation is a mathematically based on linear programming, it requires the professional knowledge of animal nutritionists who take into consideration the nutrient composition of feed ingredients as well as the animals feed requirements and capability to digest certain food. Extensive research was done to ensure that the nutrient requirements and the food compatibilities are of the latest research applicable to animal diets. As with in any field of research, values change, people become more intelligent and their resources improve. To accommodate this change, all requirements that are included as constraints are set as variables which may be changed by the nutritionist if necessary.

### 3.1 Outputs of the feed formulation

The goal of this project is to determine least-cost diets for animals given certain nutritional requirements are met. Thus the output is denoted as follow:

$x_{ij} \triangleq$  amount(in kg) of food  $i$  given to animal type  $j$  where  $i \in \{1 \dots 15\}$  and  
 $j \in \{1 \dots 150\}$

The next output determines the total amount of feed ingredient  $i$  necessary to feed all the animals for a week.

$s_i \triangleq$  amount of food  $i$  required to feed all the animals for a week

## 3.2 Inputs for the feed formulation

Rossi (2007) states that a least-cost feed formulation model is effective if it offers the following basic features that are applicable to all animal species. It is important to take into account the effect which the nutritionist has on the model, the feed formulation runs on data that is entered into an interface by the nutritionist, therefore, making the model only as accurate as the information that is entered into the model interface.

### 1. Available Ingredients

The model will run through an excel interface providing a way of entering and managing the ingredients which are available for inclusion in the formulation. Available feed ingredients are listed along with their unit price( in rand) in Figure 3.1. The

<b>F o o d</b>	<b>D e s c r i p t i o n</b>	<b>C o s t / K g</b>
1	B e e f C a r c a s s	1 1 . 4
2	C h i c k e n	2 1
3	C h i c k s	8
4	B e e f H e a r t M i n c e	1 8
5	C a t f o o d	8 0
6	H o r s e M e a t	1 6 . 9 5
7	R a b i t	2 1
8	M a a s b a n k e r	7 . 9 5
9	H a k e	1 4 . 5
10	S a r d i n e s	6 . 3 5
11	R i b b o n F i s h	7 . 5
12	L u c e r n e	2
13	T e f f	1 . 6 8
14	B o s k o s	1 . 8 2
15	A n t e l o p e	2 . 1 6

Figure 3.1: Available food ingredients and their unit price

following denotes the feed ingredients and their associated cost:

$$c_i \triangleq \text{given cost(per kg) of food type } i \in \{1 \dots 15\}$$

### 2. Nutrient Composition

Each feed ingredient available for inclusion in the formulation should have corresponding nutrient composition data. The nutritional components include protein fat and fibre. These values form part of the interface and is shown in the Figure 3.2.

The feed ingredients and their associated nutrient compositions are denoted as follow:

$$v_{ip} \triangleq \text{given nutritional value of component } p \text{ in feed ingredient } i$$

where  $i \in \{1 \dots 15\} \cup p \in \{1 \dots 3\}$

The energy is not taken as a nutrient but is only included in the same part of the interface to make the interface more user friendly. The feed ingredients' energy is

denoted as:

$k_i \triangleq$  given amount of energy(in kJ) supplied by a kilogram of food  $i$

		Nutritional component			
		p			Energy(kg)
		Protein	Fat	Fibre	
Food i		1	2	3	
	1	Beef Carcass	0.22	0.17	0
2	Chicken	0.18	0.13	0	2270
3	Chicks	0.17	0.16	0	1480
4	Beef Heart Mince	0.17	0.37	0	1170
5	Catfood	0.33	0.22	0	4480
6	Horse Meat	0.214	0.046	0	1270
7	Rabbit	0.192	0.044	0	2190
8	Maasbanker	0.196	0	0	8276.4
9	Hake	0.1909	0	0	5601.2
10	Sardines	0.1766	0	0	6897
11	Ribbon Fish	0.1448	0	0	4012
12	Lucerne	0.1836	0	0.2503	9000
13	Teff	0.1091	0	0.3033	7500
14	Boskos	0.098	0	0.0623	8000
15	Antelope	0.115	0	0.156	8000

Ratios for antelope foraging	
Lucerne	0.40
Teff	0.40
Boskos	0.20
Antelope	0.00

Figure 3.2: Nutrient Composition

### 3. Formulation specifications

The specifications define the desired nutrient levels that should be met in the animal diets when running the model. There are also specifications as to what levels of feed ingredients or ratios between feed ingredients should be included.

Lower limits and upper limits are set for each nutrient requirement and ingredient. This is done for energy as well as the nutrient levels. The specified nutrient levels are denoted as follow:

$$\bar{r}_{jp} \triangleq \text{maximum allowable percentage of component } p \text{ in animal type } j\text{'s diet}$$

where  $j \in \{1 \dots 150\} \cup p \in \{1 \dots 3\}$

$$\underline{r}_{jp} \triangleq \text{minimum allowable percentage of component } p \text{ in animal type } j\text{'s diet}$$

where  $j \in \{1 \dots 150\} \cup p \in \{1 \dots 3\}$

The specified energy requirement is denoted as:

$$\underline{e}_j \triangleq \text{given minimum energy requirement for animal type } j$$

$$\bar{e}_j \triangleq \text{given maximum energy requirement for animal type } j$$

The above values are available electronically on the CD.

The following inputs are more specific to the requirements set by the nutritionist at the Joburg Zoo.

The BMR values allow the nutritionist to set each and every animal's physical condition to a certain factor depending on the whether the animal is normal, growing, underweight or lactating. It is denoted as follow:

$$b_j \triangleq \text{given body mass ratio of animal type } j$$

Carnivores and omnivores do not eat seven days a week. To determine the amount of food required for a week the next input is included and also changeable on the interface.

$$t_j \triangleq \text{the number of times animal type } j \text{ is fed per a week}$$

The last input enables the nutritionist to set a ratio between the feed ingredient which antelope and pachyderms feed on. These values can be set on the interface as in Figure 3.2.

$$g_i \triangleq \text{the intake(in percentage) between food } i \text{ where } i \in \{12 \dots 15\}$$

### 3.3 Defining subsets

Due to the diverse food compatibility of the animals and the large amounts of different species, subsets are defined to simplify the formulation equations. A graphical explanation(see Appendix A.3) of the grouping of animals clarify the reasons as to why subsets are defined. The subsets are formed from the set below.

$$j = 1 \dots 150$$

The first subset refers to all the large cats and omnivores that are allowed the same feed ingredients.

$$j^l \subseteq j$$

The following subset refers to all the animal types that are not allowed to eat fish. The subset is formed because quite a few animals from different animal groups are allowed fish. It simplifies the formulation equations in the instances where an omnivore or carnivore requires a diet comprising only of fish.

$$j^n \subseteq j$$

A subset is also formed that includes all the animal types which are allowed fish.

$$j^f \subseteq j$$

The next 3 subsets refer specifically to the combination set which combines the feed ingredients and the animal types. The set is called combination but will be referred to with an "m" in the notation below. All animal types which has a m2 behind it on the interface, refers to the specific species that is in need of a second diet. The next subset refers to the combinations of animals and feed ingredients which cannot form part of the second diet.

$$m^{m2} \subseteq combination(i, j)$$

The following subset is for the few animals that have a m3 behind it on the interface. It specifically refers to the combination of all the animals and the feed ingredients that must not be taken into consideration when working out the least cost diets for animals that have a third diet.

$$m^{m3} \subseteq combination(i, j)$$

The next subset refers to all the small carnivores and small omnivores that forage from the same feed ingredients. A combination of all the small animals and the feed ingredients which they are not allowed to eat is defined below.

$$m^s \subseteq (i, j)$$

The subsets with their associated j values and (i,j) values are fully written out in Appendix A.2.

### 3.4 Objective function

The objective function ensures that the cost of a diet is minimized. The total cost of any diet may be determined by the following relation:

$$(\text{total cost of diet}) = (\text{cost of food 1}) + (\text{cost of food 2}) + (\text{cost of food 3}) \dots$$

To evaluate the total cost of a diet, note that, for example,

$$\text{Cost of beef} = (\text{Amount of Beef eaten(in kg)}) \left( \frac{\text{cost}}{\text{kg of beef}} \right)$$

By applying this to all the foods, the objective function (3.1) is formulated as follow:

$$\min z = \sum_{i=1}^{15} \sum_{j=1}^{150} x_{ij} c_i$$

### 3.5 Equations for the formulation

$$\min z = \sum_{i=1}^{15} \sum_{j=1}^{150} x_{ij} c_i \quad (3.1)$$

subject to

Equations (3.2) and (3.3) ensure that the energy requirement is met while (3.4) and (3.5) ensure the nutrient requirements are met.

$$\sum_{i=1}^{15} k_i x_{ij} \geq \underline{e}_j b_j \quad \forall j \in \{1 \dots 150\} \quad (3.2)$$

$$\sum_{i=1}^{15} k_i x_{ij} \leq \bar{e}_j b_j \quad \forall j \in \{1 \dots 150\} \quad (3.3)$$

$$\sum_{i=1}^{15} v_{ip} x_{ij} \geq \bar{r}_{jp} \sum_{i=1}^{15} x_{ij} \quad \forall j \in \{1 \dots 150\} \cup p \in \{1 \dots 3\} \quad (3.4)$$

$$\sum_{i=1}^{15} v_{ip} x_{ij} \leq \underline{r}_{jp} \sum_{i=1}^{15} x_{ij} \quad \forall j \in \{1 \dots 150\} \cup p \in \{1 \dots 3\} \quad (3.5)$$

The following equations (3.6),(3.7),(3.8),(3.9),(3.10),(3.11), ensure that all the animals eat the feed ingredients that are compatible to their species. The groups are defined as subsets in Appendix A.2.

$$x_{ij} \leq 0 \quad \forall i \in \{3 \dots 5\} \cup j \in j^l \quad (3.6)$$

$$x_{ij} \leq 0 \quad \forall i, j \in m^s \quad (3.7)$$

Most carnivores and omnivores have more than one diet so that they have a variety in their diets. All the animals with a m2 behind the animal type j on the interface refers to

a second diet. Equation (3.8) ensures that this is met:

$$x_{ij} \leq 0 \quad \forall i, j \in m^{m^2} \quad (3.8)$$

$$x_{ij} \leq 0 \quad \forall i, j \in m^{m^3} \quad (3.9)$$

$$x_{ij} \leq 0 \quad \forall i \in \{1 \dots 7\} \cup j \in j^f \quad (3.10)$$

$$x_{ij} \leq 0 \quad \forall i \in \{8 \dots 11\} \cup j \in j^n \quad (3.11)$$

Equation (3.12) ensures that the model does not consider grass or pellets for any carnivore or omnivore. Equation (3.13) ensures that antelope and pachyderm diets only consist of grasses or pellets.

$$x_{ij} \leq 0 \quad \forall i \in \{12 \dots 15\} \cup j \in \{1 \dots 98\} \quad (3.12)$$

$$x_{ij} \leq 0 \quad \forall i \in \{1 \dots 11\} \cup j \in \{99 \dots 150\} \quad (3.13)$$

To ensure that the antelope and pachyderms get the specified ratio between grasses and pellets the following equations (3.14) - (3.17) are included:

$$x_{12j} = g_1 \sum_{i=1}^{15} x_{ij} \quad \forall j \in \{99 \dots 150\} \quad (3.14)$$

$$x_{13j} = g_2 \sum_{i=1}^{15} x_{ij} \quad \forall j \in \{99 \dots 150\} \quad (3.15)$$

$$x_{14j} = g_3 \sum_{i=1}^{15} x_{ij} \quad \forall j \in \{99 \dots 150\} \quad (3.16)$$

$$x_{15j} = g_4 \sum_{i=1}^{15} x_{ij} \quad \forall j \in \{99 \dots 150\} \quad (3.17)$$

Seals must have three different diets, each of the following equations eliminate certain feed ingredients to ensure a variety of diets:

Male seals:

$$x_{9,57} + x_{10,57} + x_{11,57} \leq 0 \quad (3.18)$$

$$x_{8,58} + x_{10,58} + x_{11,58} \leq 0 \quad (3.19)$$

$$x_{9,59} + x_{11,59} + x_{8,59} \leq 0 \quad (3.20)$$

Female seals:

$$x_{9,60} + x_{10,60} + x_{11,60} \leq 0 \quad (3.21)$$

$$x_{8,61} + x_{10,61} + x_{11,61} \leq 0 \quad (3.22)$$

$$x_{8,62} + x_{9,62} + x_{11,62} \leq 0 \quad (3.23)$$

The variable  $s_i$  is determined in order to obtain the amount of food  $i$  that should be available each week. A buffer of 30% is added to this variable so that there is a backup whenever food is not available within one day. The 30% buffer amount covers 2.7 day's of food supply needed. The food will work on a basis of First-In-First-Out to ensure that the buffer amount exits the stores first.

$$s_i = 1.3 \sum_{j=1}^{15} x_{ij} t_j \quad \forall j \in \{1 \dots 150\} \quad (3.24)$$

Once all the above necessary information is provided, the feed formulation will produce the desired, least cost diets that adhere to all the requirements.

## Chapter 4

# Execution and analysis of results

The model was executed on Lingo and the algorithm is available electronically on the attached CD. The data required to execute the model is also available electronically and the spreadsheet is also the interface on which the nutritionist is able to change values of the number of animals, weight, body mass ratios, ratios between grass and pellet intake, cost of food, required % of nutrients as well the number of times an animal is fed a certain diet. A part of the carnivore interface is available in Appendix B.1 for illustration purposes.

When the model is run the results are exported onto an excel spreadsheet. An example of some of the filtered results containing all values which are not zero is available in Section 5.1. The complete results are all on the CD which is attached to the project book. These results will have to be documented by the nutritionist and further reworked into diet sheets which are handed to the various animal keepers.

The verification and validation processes are explained in this chapter where after the execution process is explained in detail in Section 4.2. The results are analyzed after the execution and a sensitivity analysis is conducted in Section 4.4.

### 4.1 Verification and Validation

While executing the model, constant verification is done through de-bugging. Error messages within Lingo serve as guidance to identify the problems.

Validation is present throughout the process. Meetings are frequently held with the nutritionist in order to evaluate the validity of the input data and results. A questionnaire (see A.1) is also completed for each group of animals to further ensure that all relevant data is present. This is very important as all data is gathered in meetings where many important facts are brought across by speaking with the nutritionist.

More validation is done by comparing the results to the Zoo's current diets, this gives a clear indication of whether the results are realistic or not.

After verification and validation the results are sure to be sufficient and reliable. This does not mean that it necessarily practical to implement. After analyzing the results, one should be sure to either implementing the model or discard it.

## 4.2 Model Execution

The outcome of the model executed with all the requirements set by the nutritionist was infeasible. The requirements were given priorities because it was speculated that the requirements might be too idealistic and may only be met if a large variety of food is available. The food types considered in this project does not only include the current food that is used by the zoo but also considers food that is known to be available and that can be a realistic option to consider. (Refer to Section 1.5 for the definition of a realistic diet)

The main constraint is that of the energy limitations. This constraint ensures that an adequate amount of kilojoules are consumed. These constraints were all met with no infeasibility.

Clearly some of the nutritional component percentages could not be met. This is due to the limit on available food ingredients and their associated nutrient component percentages. The food available is not nutritionally sufficient to meet all the set requirements. The nutrient components which caused the infeasibility were identified by increasing the upper and lower required component percentage and through trial and error finding the following:

The required protein percentage was set to be greater than 26% of all carnivores and omnivores diets. However, it could not exceed 20% of the total diets.

A sensitivity analysis is conducted where all nutrient percentages are changed to determine the effect it has on the costs of the diets in Section 4.4.

## 4.3 Analysis of results

Diets from the animal groups are compared in terms of cost and energy while any other nutrient requirement that is met is considered an additional benefit.

### 4.3.1 Analysis on carnivore and omnivore diets

The comparison in Figure 4.1 show the costs of the modeled diets compared to the costs of current diets. The graphs compare all the diets and clearly indicate from an amount fed perspective, that few diets are actually correct. The total cost of these diets are shown in Figure 4.2. The cost of food, which is proportional to the amounts fed, does not differ that excessively for the individual animal diets, but adding it together it results in a large percentage of the total cost. If one considers that over a period of a year they could save R58347 by only changing the carnivore and omnivore diets, it is worth accurately measuring the amounts and not merely rounding it off to the highest kilogram.

Figure 4.2 indicate 2 important facts: Firstly that there are current diets which are more expensive than the modeled diets and are costing the zoo unnecessary money. The diets are also not nutritionally balanced because the animals are fed an excess of food. The same goes for the animals that are not fed enough food. Their diets are not nutritionally sufficient because they do not get the required nutrients in their current diets. Figure

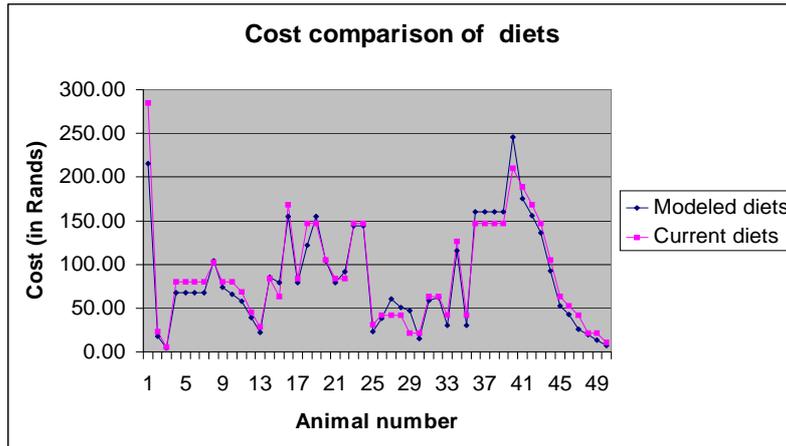


Figure 4.1: Comparing the costs of current and modeled diets

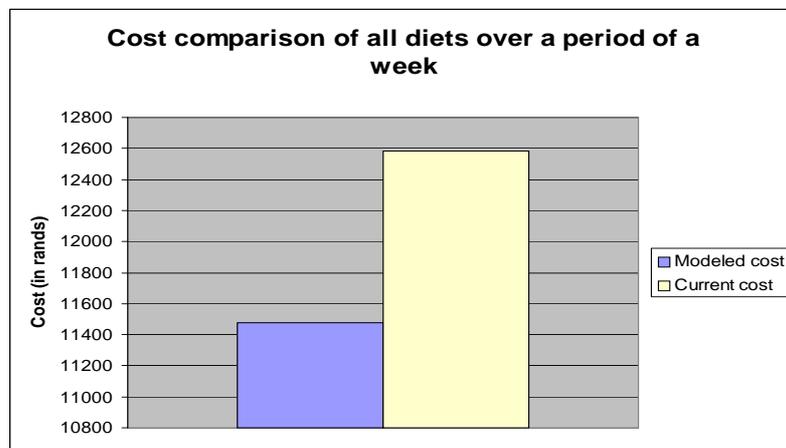


Figure 4.2: Cost comparison of all the diets over a weekly period

4.3 is another way in which the diets can be analyzed. By comparing the energy of the modeled and current diets and including the allowable energy limits, clearly shows how erroneous the current diets are worked out. The graph shows that the modeled diets fall perfectly into the maximum and minimum amounts of energy allowed.

### 4.3.2 Analysis on antelope and pachyderm diets

The antelope diets are currently worked out according to each animal's energy requirements. When the data was studied on the current diets, it was noticed that a critical problem occurred in the nutritionists' spreadsheet calculations. She had multiplied all the individual energy values with a single animals' weight instead of each of the animals' associated BMR values.

Figure 4.4 shows the cost comparison between a few animals' diet over a one day period. Only a few animals were taken so that the two lines can be easily distinguished from one another. The effect will be the same for all the antelope as their current diets are all worked out in the same erroneous way.

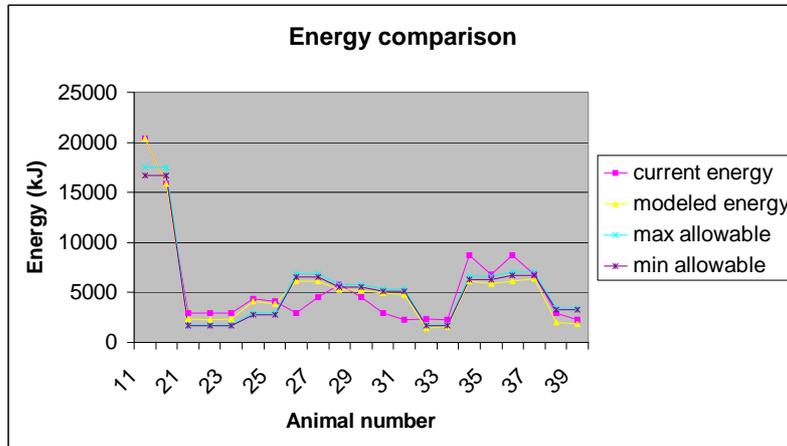


Figure 4.3: Comparing the energy levels in the diets

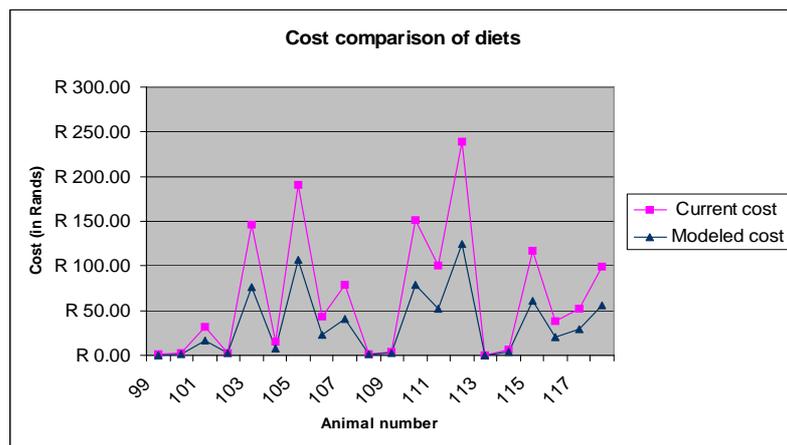


Figure 4.4: Comparing the costs of previous and modeled diets

The zoo could save up to R350800 every year if the diets are fed correctly. Figure 4.5 illustrates the comparison of cost over a yearly period. It can easily be seen from the cost that the antelope and pachyderms are unnecessarily being fed an enormous amount of food every day. The energy values are assumed to also be much higher than what is necessary.

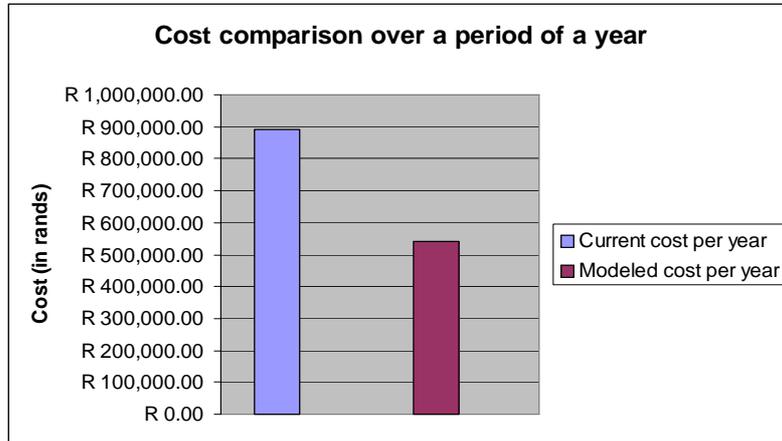


Figure 4.5: Cost comparison over a period of a year

#### 4.4 Sensitivity Analysis

The nutritionist has the option of changing each and every animal's nutrient requirements. The nutrient requirements can be changed on the interface. A segment of the interface is shown in below. Fibre is not a requirement in carnivore and omnivore diets; therefore the minimum value for fibre is set zero and the maximum at 100%.

		Nutritional Component P			Nutritional Component P			
		Maximum Amounts			Minimum Amounts			
		Protein	Fat	Fibre	Protein	Fat	Fibre	
<b>Carnivores</b>	1	Triton m1	1	1	1	0.18	0	0
	2	Triron m2	1	1	1	0.18	0	0
	3	Niobe m1	1	1	1	0.18	0	0
	4	Niobe m2	1	1	1	0.18	0	0
	5	Dharma m1	1	1	1	0.18	0	0
	6	Dharma m2	1	1	1	0.18	0	0
	7	Nyanga m1	1	1	1	0.18	0	0
	8	Nyanga m2	1	1	1	0.18	0	0
	9	Numzaan m1	1	1	1	0.18	0	0
	10	Numzaan m2	1	1	1	0.18	0	0
	11	Simone m1	1	1	1	0.18	0	0
	12	Simone m2	1	1	1	0.18	0	0
	13	Shumba m1	1	1	1	0.18	0	0
	14	Shumba m2	1	1	1	0.18	0	0
	15	Vidor m1	1	1	1	0.18	0	0
	16	Vidor m2	1	1	1	0.18	0	0
	17	Kira m1	1	1	1	0.18	0	0
	18	Kira m2	1	1	1	0.18	0	0
	19	Sabre m1	1	1	1	0.18	0	0
	20	Sabre m2	1	1	1	0.18	0	0
	21	Caracal meal 1	1	1	1	0.18	0	0
	22	Caracal meal 2	1	1	1	0.18	0	0
	23	Caracal meal 3	1	1	1	0.18	0	0
	24	Serval meal 1	1	1	1	0.18	0	0

Figure 4.6: % Nutrient requirement

In this section we look at what the effect is on the cost of diets when changing these requirements. Sensitivity analysis is not conducted on the energy requirement as it is the basic requirement that must be met.

#### 4.4.1 Protein and fat requirement analysis

The analysis is done on a few animals from all the different groups of animals which have different feed ingredient compatibilities. The protein and fat requirements are only of interest in the carnivore and omnivore group and the effect will be the same even if it is done on all the carnivores and omnivores because the feed ingredients remain the same. The table below shows what the effect was on the objective value when the protein and fat requirement percentages were changed.

Protein was said to more important than the fat requirement. The red block indicates the best nutrient % which is possible for the diets. From the table it is very clear that the protein requirement could not be met at what was said to be the initial requirement. The protein requirement is at its best when it is set at smaller than 21%. The table also indicates that the fat requirement is automatically met if the protein percentage is low. The requirements are still included in the interface and model because all the values may change if a feed ingredient is substituted for another feed ingredient that has different nutrient compositions.

		Fat %			
		ideal < 16%	<18%	< 20%	No fat requirement
Protein %	ideal < 26%	Infeasible	Infeasible	Infeasible	Infeasible
	< 22%	Infeasible	Infeasible	Infeasible	Infeasible
	< 21%	R 1,958.90	R 1,918.05	R 1,918.05	R 1,918.05
	< 20%	R 1,748.25	R 1,707.40	R 1,707.40	R 1,707.40
	< 18%	R 1,556.83	R 1,556.83	R 1,556.83	R 1,556.83

Figure 4.7: Protein and fat requirements analysis

The nutritionist will have to decide whether she wants to pay less, or whether she is willing to pay more and include the best protein % and fat% possible. Any protein % lower than 18% has no effect on any of the values. It therefore automatically includes at least 18% of the required 26% protein due to the energy requirement.

#### **4.4.2 Fibre and protein requirement analysis**

The fibre requirement for all antelope and pachyderms is to have between 35% and 12% fibre in their diet. The required protein is between 16% and 9%. Although these values were taken to a minimum of 0% and a maximum of 100% it had no effect on the objective value. This indicated that the energy requirement is enough to ensure that the fibre and protein requirements are met. These values are also kept in the interface and model for the same reason as the fat requirement.

The requirement will still be included in the formulation as the current nutrient values may change or other feed ingredients with different nutrient values can become available and may have a different effect on the objective value.

#### **4.4.3 Concluding sensitivity analysis**

It is the choice of the nutritionist to decide whether she is satisfied with only the energy requirement being met, or whether she is willing to pay more and include the nutrient requirements. If she does not want to include the nutrient requirements she can easily set all the minimum values to 0% and all maximum values to 100%. The analysis clearly indicates that the diets can be worked out at lower costs and also include most of the nutrient compositions that are required.

## Chapter 5

# Conclusion and Future Research

### 5.1 Conclusion

The goal of this project was to determine least cost diets for the animals. The analysis in Chapter 4 clearly indicated that most of the diets are not adequate and should be changed.

The analysis on the carnivore and omnivore diets indicate the importance of accurate measurements as the small corrections that can be made will result in a large amount of saved money by the end of the year.

The antelope and pachyderm diet comparisons resulted in a big surprise when the comparison revealed that something was wrong in either the model or calculations of the nutritionist. It was found that the nutritionist had made basic errors in calculating the diets. If the modeled diets are fed to the animals the zoo could save up to R350800 every year.

The model will help in achieving a well managed and comprehensive manner of obtaining the diets at least possible cost while meeting the nutrient requirements. The developed interface is also an improved way of managing the animal counts and all the relevant information required for determining animal diets. Even more so, the nutritionist is able to determine the amount of food required for a period of a week.

A part of the exported results are shown in Figure 5.1.

The exported amount of feed ingredients required for a period of a year is available in Figure 5.2.

#### 5.1.1 Recommendations

It was found at a later stage of the project that animal keepers tend to feed the animals even more food as what they are instructed to feed on the diet sheet. This is a psychological trend they follow because they feel sorry for the animals being kept in captivity. Even though the current diet sheets are not correct, if they carry on doing so with the new diets, the goal to reduced expenses will not be achieved. Strict control must therefore be taken on the accessibility of food and distribution there of. Animal keepers must also be encouraged to cooperate in feeding the animals according to the modeled diets sheets.

## Diet Results

Name	i	j	x_ij
African Elephant M	12	144	14.59571
African Elephant F	12	145	5.785773
Pigmy Hippo M	12	146	1.276631
Pigmy Hippo F	12	147	1.276631
African Hippo	12	148	8.537347
White Rhino M	12	149	4.268674
White Rhino F	12	150	5.046328
mouse deer	13	99	0.13579
grey duiker	13	100	0.269975
red hartebeest	13	101	3.670626
red deer	13	102	0.615409
s. h. oryx	13	103	16.69997
B zebra	13	104	1.794756
water buffalo	13	105	23.28072
blackbuck	13	106	4.929271
bongo	13	107	8.973781
red duiker	13	108	0.18405
steenbok	13	109	0.43516
african buffalo	13	110	17.17623
nyala	13	111	11.3849
eland	13	112	27.16567
springbok	13	114	0.731849
waterbuck	13	115	13.26714
arabian oryx	13	116	4.365135
sitatunga	13	117	6.319002
sable	13	118	12.14543
hog deer	13	119	2.969721
bushbuck	13	121	9.671682
blackbuck	13	122	2.147029
bontebok	13	123	2.290811
lord derby eland	13	124	15.53939
sable	13	126	3.036358
bactrian camel	13	128	12.76631
guanaco	13	129	4.848026

Figure 5.1: Examples of optimal diet results

<b>Food</b>	<b>S<sub>i</sub> (in Kg)</b>
Beef Carcass	361.25
Chicken	286.79
Chicks	52.13
Beef Heart Mince	6.94
Catfood	0.00
Horse Meat	0.00
Rabit	0.00
Maasbanker	24.46
Hake	36.14
Sardines	90.50
Ribbon Fish	0.00
Lucerne	2300.86
Teff	2300.86
Boskos	1150.43
Antelope	0.00

Figure 5.2: Food required for a period of a week

The current diets are not revised often enough. If the model is implemented, continuous updating on animal counts and their relevant information is required. The process may seem time consuming, but given the interface which already includes all the relevant information, the nutritionist will find the process less time consuming than expected.

## 5.2 Future Research

The project only covered the animals' diets that forage off the feed ingredients that contribute 75% of the cost of feeding the animals. Future research may involve research on animals that feed off vegetables and produce.

Multi-blending can also be incorporated as future research. It involves solving the problem when having a limited amount of some feed ingredient. An advanced feature of some least-cost feed formulation packages may include multi-blending. The multi-blending takes into consideration the ingredients that are available in limited quantities. The model should then optimize the allocation of the scarce ingredients to different equations in order to achieve the total least-cost solution.

The improvement of the procurement strategy is also a possible area for future research. The weekly amount of feed ingredients that are required to feed the specified animals involved, was adequate for this project. If fruit or vegetables are taken into consideration for determining animal diets and developing a procurement strategy, the food wastage and expiry dates have to be considered. A multiperiod decision problem can be brought into the existing model to determine the demand and at what specific time.

In conclusion, if the Jhb zoo wants to accomplish their mission of becoming a world class zoo, the first area of concern is that of the animal's welfare. The project contributes

to some major important problem areas especially in carnivore, omnivore, antelope and pachyderm diets.

# Appendix A

## Data

### A.1 Questionnaire for data gathering

The questionnaire has been completed for all animal groups.

1. What is the group name for the animals?
2. What is the energy calculation of the animal group?
3. Are there any subgroups of animals within the group? Explain what the subgroups have in common.
4. What are the names of the animals in each group or subgroup?
5. What is each animal's associated: average weight as adult?
6. What foods are consumed by the group of animals?
7. Are there any exceptions as to animals that may not consume a specific food? Or if it is a subgroup exception please specify.
8. What are the important nutrient intake that must be met within the group?
9. What are each food's related nutritional values? As indicated in your answer in question 8.
10. Are there any other important forage information I need to know to be able to know what each animal's nutritional requirements are?

## A.2 Defining subsets

$$j^l = j \in \{1 \dots 20\} \cup j \in \{26 \dots 31\} \cup j \in \{34 \dots 37\} \cup j \in \{40 \dots 43\} \\ \cup j \in \{49 \dots 56\} \cup j \in \{68 \dots 69\} \cup j \in \{71, 72, 74, 75, 77, 78, 80, 81\}$$

$$j^n = j \in \{1 \dots 56\} \cup j \in \{68, 69, 71, 72, 74, 75, 77, 78, 80, 81, 83, 84\} \\ \cup j \in \{86 \dots 98\}$$

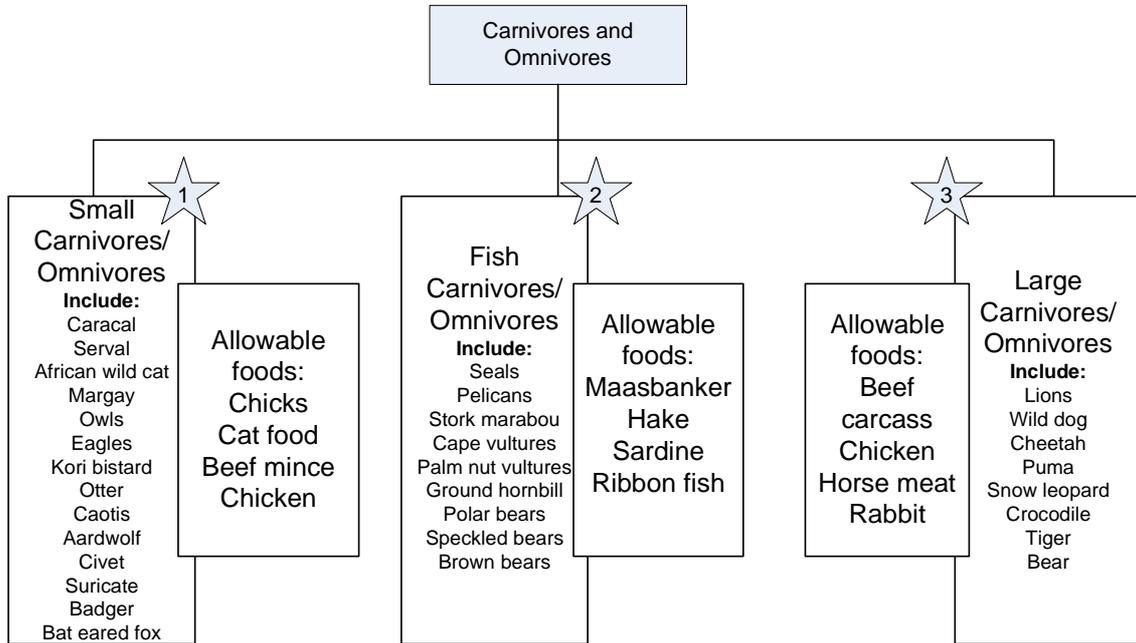
$$j^f = \in \{57 \dots 67\} \cup j \in \{70, 73, 76, 79, 82, 85\}$$

$$m^{m2} = i, j \in \{1\ 2, 1\ 4, 1\ 6, 1\ 8, 1\ 10, 1\ 12, 1\ 14, 1\ 16, 1\ 18, 1\ 20, 3\ 22, 3\ 25, 1\ 27, \\ 1\ 19, 1\ 29, 1\ 31, 3\ 33, 1\ 35, 1\ 37, 3\ 39, 1\ 41, 1\ 43, 1\ 48, 1\ 53, 1\ 54, 1\ 55, 1\ 56, 1\ 69, 1\ 72, \\ 1\ 75, 1\ 78, 1\ 81, 1\ 84, 1\ 87, 1\ 89, 1\ 91, 1\ 94, 1\ 96, 1\ 98, 3\ 87, 3\ 89, 3\ 91, 3\ 94, 3\ 96, 3\ 98\}$$

$$m^{m3} = i, j \in \{2\ 23, 3\ 23, 2\ 92, 3\ 92\}$$

$$m^s = i, j \in \{1\ 21, 1\ 22, 1\ 23, 1\ 24, 1\ 25, 1\ 32, 1\ 33, 1\ 38, 1\ 39, 1\ 86, 1\ 87, 1\ 88, 1\ 89, 1\ 90, \\ 1\ 91, 1\ 92, 1\ 93, 1\ 94, 1\ 95, 1\ 96, 1\ 97, 1\ 98, 6\ 21, 6\ 22, 6\ 23, 6\ 24, 6\ 25, 6\ 32, 6\ 33, 6\ 38, \\ 6\ 39, 6\ 86, 6\ 87, 6\ 88, 6\ 89, 6\ 90, 6\ 91, 6\ 92, 6\ 93, 6\ 94, 6\ 95, 6\ 96, 6\ 97, 6\ 98, 7\ 21, 7\ 22, \\ 7\ 23, 7\ 24, 7\ 25, 7\ 32, 7\ 33, 7\ 38, 7\ 39, 7\ 86, 7\ 87, 7\ 88, 7\ 89, 7\ 90, 7\ 91, 7\ 92, 7\ 93, 7\ 94, \\ 7\ 95, 7\ 96, 7\ 97, 7\ 98\}$$

### A.3 Illustration of the animal groups



This group of animals are set as a subgroup and is referred to as "small" in the model formulation



This group of animals are set as a subgroup and is referred to as "fish" in the model formulation



This group of animals are set as a subgroup and is referred to as "large" in the model formulation

Figure A.1: Animal groups and compatible feed ingredients

## Appendix B

# Excel Interface

### B.1 Interface

	Nr	Animals	BMR	avg weight (in kg)	Energy req. per animal	nr of animals	Total_kJ	eUL	eLL	nr of times fed per week
<b>Carnivores</b>	1	Triton m1	1	100	9252.824434	1	9252.82	9715.47	9252.82	2
	2	Triron m2	1	100	9252.824434	1	9252.82	9715.47	9252.82	2
	3	Niobe m1	1	90	8549.804886	1	8549.80	8977.30	8549.80	2
	4	Niobe m2	1	90	8549.804886	1	8549.80	8977.30	8549.80	2
	5	Dharma m1	1	220	16714.42083	1	16714.42	17550.14	16714.42	2
	6	Dharma m2	1	220	16714.42083	1	16714.42	17550.14	16714.42	2
	7	Nyanga m1	1	90	8549.804886	1	8549.80	8977.30	8549.80	2
	8	Nyanga m2	1	90	8549.804886	1	8549.80	8977.30	8549.80	2
	9	Numzaan m1	1	160	13163.28574	1	13163.29	13821.45	13163.29	2
	10	Numzaan m2	1	160	13163.28574	1	13163.29	13821.45	13163.29	2
	11	Simone m1	1	220	16714.42083	1	16714.42	17550.14	16714.42	2
	12	Simone m2	1	220	16714.42083	1	16714.42	17550.14	16714.42	2
	13	Shumba m1	1	130	11265.0166	1	11265.02	11828.27	11265.02	2
	14	Shumba m2	1	130	11265.0166	1	11265.02	11828.27	11265.02	2
	15	Vidor m1	1	90	8549.804886	1	8549.80	8977.30	8549.80	2
	16	Vidor m2	1	90	8549.804886	1	8549.80	8977.30	8549.80	2
	17	Kira m1	1	110	9938.454085	1	9938.45	10435.38	9938.45	2
	18	Kira m2	1	110	9938.454085	1	9938.45	10435.38	9938.45	2
	19	Sabre m1	1	200	15561.33379	1	15561.33	16339.40	15561.33	2
	20	Sabre m2	1	200	15561.33379	1	15561.33	16339.40	15561.33	2
	21	Caracal meal 1	1.5	10	1645.410718	1	1645.41	1727.68	1645.41	1
	22	Caracal meal 2	1.5	10	1645.410718	1	1645.41	1727.68	1645.41	1
	23	Caracal meal 3	1.5	10	1645.410718	1	1645.41	1727.68	1645.41	1
	24	Serval meal 1	1.5	8	1391.848007	2	2783.70	2922.88	2783.70	1

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