Evaluating a selection index for improving body weight and egg

production in a simulated population of broilers

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ABSTRACT

The most successful method used for improving the growth rate of broilers is genetic selection. Improvements in nutrition, housing and disease resistance have been impressive, yet genetic selection is purported to have contributed the majority of the tremendous increase in growth rate that has taken place over the past 50 years (McKay, 2008). Many selection strategies are available, but not all are suitable, as the choice is dependent on the objective of the breeder. Selection strategies are bound to change over time as different traits become more important, and this has been the case in the broiler industry: focus was initially placed predominantly on growth rate, but the negative genetic correlation that exists between growth rate and reproductive and liveability traits has forced breeders to change their position, especially as growth rate has almost reached its upper limit and reproductive traits lag behind. This has resulted in a change from single trait to multiple trait selection.

In the exercise reported here, four selection strategies commonly used for single trait selection, namely individual, between family, within family and family-index selection, were applied to a simulated broiler population using the Monte Carlo method of simulation, and constructed with the use of genetic parameters obtained from the literature. Theoretical and simulated methods of the four selection strategies were compared. A fifth selection strategy, index selection, was applied to represent multiple trait selection. The relative merit of each selection procedure was then compared, as well as the results obtained from the theoretical and simulated methods. Construction of the selection index was complex in comparison to single trait selection, as each trait included in the index had to be assigned an economic value. This value is representative of the relative importance of that trait to the overall profitability, or ability to save costs in the operation. Therefore traits favourable to profitability, or having the ability to reduce production costs, are given a heavier weighting and will consequently achieve a relatively larger improvement when applied to the selection index. A model was constructed using production rates, income and costs to represent the current overall economic situation in the industry. This was then used to determine cost economic values, which represent the saving in cost per unit improvement in each of the economically important traits, and revenue economic values, calculated as the value of each unit improvement attained in each of the economically important traits.

Body weight remains the most profitable trait in a broiler enterprise; however breeder egg production is equally important as the industry would fail without sufficient day-old broilers. Therefore, it would be beneficial to determine whether current egg production levels could be maintained, or even improved, whilst improvement is made to the growth rate of the progeny.

The above statement was found to be possible with the use of index selection. This multiple trait selection strategy proved capable of defying the negative genetic correlation that exists between body weight and egg production by improving egg production to 60 weeks by eight eggs, and body weight at 35 days by 259 grams. Furthermore, in some cases index selection was able to achieve improvements in some traits greater than those attained with single trait selection, whilst simultaneously improving certain negatively correlated traits. Index selection has illustrated its superiority over single trait selection strategies and its relative value to the poultry industry.

PREFACE

The experimental work described in this dissertation was conducted in the School of Agricultural Sciences and Agribusiness, University of KwaZulu-Natal, Pietermaritzburg, from February 2007 to December 2009, under the supervision of Professor Rob Gous.

The results have not been submitted in any other form to another university and except where the work of others is acknowledged in the text, the results are of my own investigation.

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Justine Tempest

27 January 2010

I certify that the above statement is correct.

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Professor Rob Gous

Supervisor

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

INTRODUCTION

It is relatively simple to impress laymen when discussing the broiler industry. An example is to compare the length of time that it took for a broiler 50 years ago to reach 1.8 kg in weight (120 d) with the 32 d in 2009. If that doesn't do the trick, you can always follow with the illustration of the difference in weight between a broiler and laying hen, two birds of the same descent! It is for this reason that I have chosen the exciting, dynamic field of the broiler industry to perform my research, as it is an industry that has achieved and surpassed all expectations.

As with most things in life, the beginning is relatively easy and great results are produced with very little effort. However, given that the industry is near retirement in human years, it requires more effort and attention. Continued success in the industry is dependent upon maintaining the genetic superiority of the broiler. Up to approximately five years ago, genetic superiority meant focussing on growth traits, but this view has been forced to change. The negative genetic correlation that exists between growth and reproductive traits has meant reproductive traits are now demanding more attention.

Although fast growth rate is the most important trait in determining the profitability of the broiler industry, deterioration in egg production of the broiler breeders will certainly see a lapse in the industry, as the cost of producing healthy day-old chicks is not insubstantial. So the question lies, where would you put your money: on egg production or growth rate? The answer is simple in a non-integrated operation, since the interest of the producer in each sector will lie in their own product. However, the integrated operation is faced with this dilemma.

There are various breeding methods available to suit the producer's personal breeding objectives. The method of choice prior to the dilemma mentioned above was single trait selection, and it resulted in the remarkable progress that was achieved in increasing the rate of body weight gain of the broiler. Employing these selection procedures, however, has little regard for traits negatively correlated with body weight. Four selection strategies representative of single trait selection will be constructed, namely individual, between family, within family and family-index selection. Theoretical and simulated methods of the four

selection strategies will also be compared. The relative efficiencies of each method will be illustrated on a simulated population of broiler breeders and compared using contemporary starting values and genetic parameters from the literature.

Given that single trait selection does not address these pressing issues, and it is imperative that egg production of the breeders does not deteriorate any further, multiple trait selection must be applied. The chosen strategy for this study is index selection, taking economic values (EV) and genetic parameters into account. The genetic parameters were obtained from the literature, while a model was constructed in order to calculate the EV's of chosen economically important traits. Data regarding production rates, costs and income were obtained from various farmers in each sector of the industry in the KwaZulu-Natal region in order to calculate the EV's. Cost and revenue EV's were calculated to represent the benefit of both a saving in cost and additional income. The cost EV's were represented by a saving in production costs rather than an increase in profit per unit improvement in each trait, a method which is supported by (Smith *et al.*, 1986). Furthermore, an assumption was made that an improvement in each trait will have no effect on the scale of production, but will only decrease production costs, similarly to studies from the literature (Pasternak *et al.*, 1986; Shalev & Pasternak, 1983). The revenue EV's examined the value of each unit improvement achieved in each of the economically important traits, as has also been investigated in the literature (Brascamp *et al.*, 1985; Moav & Hill, 1966). Both a saving in cost and additional income were considered in the current study.

The use of index selection gives accurate weighting to traits based on their EV to the industry, or in the case of this study, their ability to save costs and their general value to an operation. Therefore the progress made in traits will be dependent on their economic and genetic value. A sensitivity analysis was performed, manipulating traits to determine if egg production can be maintained, or increased simultaneously to growth rate.

Very few studies have been performed on single trait selection alone. More studies have focused on the comparison of certain single trait selection procedures with multiple trait selection procedures (Garwood & Lowe, 1979; Hazel & Lush, 1943; Kinney *et al.*, 1970). Comparatively more experimental studies have delved into the topic of index selection (Akbar *et al.*, 1984; Hanson & Johnson, 1957; Hazel, 1943; Lin, 1978; Nordskog, 1978) and EV's (Akbar *et al.*, 1986; Brascamp *et al.*, 1985; de Vries, 1989; Groen, 1988; Groen *et al.*, 1998;

Jiang *et al.*, 1998; Pasternak *et al.*, 1986; Shalev & Pasternak, 1983; Smith *et al.*, 1986). A few authors combined index selection and EV's (Hogsett & Nordskog, 1958; Smith, 1983).

There is no evidence of any studies combining all of the above, or any recent studies performed on index selection or the calculation of EV's. Given that EV's are not static, it is important that they are re-calculated often with contemporary inputs. Moreover, the broiler industry is one in which the only constant is change, therefore it is imperative that these EV's are updated often. Smith (1983) reiterated that a loss of efficiency in an index can occur if large changes in economic weights are not accounted for or updated.

The objective of my study was to determine to what extent it may be worth trying to increase egg production in broiler breeders whilst retaining the rapid growth rate in the progeny, considering that these traits are negatively correlated. The way in which this was done was to evaluate the genetic economic value (GEV) of the two main traits as well as other traits that may be correlated with these, including age at first egg (AFE), fertility, hatchability, mortality, feed conversion ratio (FCR) and egg weight.

The thesis includes a review of literature relating to the inception of the industry and the progress achieved in its lifespan. Information regarding the structure of the industry, the breeding plan used by the industry to produce the hybrid broiler, as well as an overview of the number of birds required from each respective line are included. Simulation modelling, heritability, genetic correlation, EV's and the different selection strategies employed in the thesis are discussed. Finally, the consequences of the monumental progress that has been achieved is also discussed.

The chapter to follow focuses on the construction of single trait selection procedures, and includes results from the application of these strategies as well as a discussion based on the results. The next chapter consists of two parts, one dealing with the calculation of EV's, and the other the construction of the selection index. Explanation of the construction of the model and the selection index is included, as are the results and discussion, comparing the results from single trait and index selection. Finally a general discussion follows in which the results from the above chapters are summarised.

CHAPTER 1

A REVIEW OF LITERATURE RELATING TO THE BROILER INDUSTRY CRISIS: THE CHICKEN OR THE EGG?

1.1 Introduction

The broiler industry was not always distinct from the laying industry, in fact, poultry meat was once a rare luxury and only a by-product from commercial egg production (Yamada, 1988). It was only the 1940's in United States and the 1950's in Europe that marked the beginning of the poultry meat industry and its separation from the egg-producing industry. The progress that has been achieved in the performance of the broiler since the establishment of this unique industry would most certainly have surpassed all expectations. Questions relating to how much more and how much longer the rate of broiler growth can continue to increase are often raised. Pollock (1999) boldly extrapolated growth trends 75 years into the future, stating the obvious danger of this exercise, predicting a 2.0 kg broiler at day one! Even though this result is highly unlikely, it illustrates the kind of improvements the broiler industry has been achieving. The improvements being made in time taken to reach 1.8 kg liveweight and the amount of feed required per kg of gain for the past 50 years are given in Table 1.1.

Table 1.1 Improvements to time to reach target weight and total feed required per kg of gain over a period of 50 years (Professor R.M. Gous, 2009, Pers. Comm.[1])

Period	Days to 1.8 kg	Food per unit gain
1950	84	3.25
1960	70	2.50
1970	59	2.20
1980	51	2.10
1990	42	1.93
2000	36	1.55

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The principal reason for the separation of egg and meat producing lines is the contrasting purposes for which they are required. Laying hens are required to produce eggs and therefore do not need to grow rapidly or be large at maturity. Broilers, however, are required to produce meat rapidly and of an acceptable composition, thus egg production does not bear as much significance. Selection criteria have consequently been directed towards these respective traits in order to improve their performance and value. While vast improvements have been achieved in their respective performance, both lines have been affected by correlated responses to selection.

The most significant genetic correlation that haunts the broiler industry is the negative genetic correlation between growth and reproductive traits. This negative relationship was recognised over 40 years ago in the chicken (Maloney *et al.*, 1967). Genetic progress achieved in the parent flock will affect profitability directly through chick costs, and indirectly through correlated responses to selection in the broiler progeny (Strain & Nordskog, 1962a). If adult body size carried a large weight in the selection programme, broiler growth rate would benefit; however, egg production of the parent flock would be adversely affected. Yet, a large selection pressure on egg production in the parent flock would prove unfavourable to the rapid growth rate of the progeny. Strain and Nordskog, (1962a) therefore questioned what the optimum level of egg production rate and adult body weight would be to maximise profit in a broiler operation. Moav & Moav (1966) attempted to answer this question by performing a study in which the objective was to determine the dependence that broiler profits have on the reproductive performance of the parent stock and the efficiency of meat production by the progeny. Undoubtedly both genetic and economic factors must be considered when answering this question. Genetic progress in a certain trait does not automatically translate to improved profit potential of the enterprise. The profit potential may increase, or decrease, depending on the genetic correlation and prices (Strain & Nordskog, 1962a), so the GEV of the trait.

Several studies have been initiated to determine the importance of different factors in broiler production (Strain & Nordskog, 1962b). It has become apparent that net income of a broiler enterprise is affected by both the performance traits of the parent stock, as well as those of the broiler progeny. Smith (1964) reiterated the basis of meat production, being the reproductive performance of the dam and the productive or growth characteristics of the progeny. Knowledge of the relative importance of these factors to the profitability of a strain of broilers is most desirable as it can be used to evaluate the economic merit of breeding

stock (Moav & Moav, 1966). It is particularly desirable to determine whether it is really worth trying to increase the number of eggs per hen, knowing that this trait is negatively related to growth rate.

Each broiler operation is unique, and is exposed to a distinct environment and situation. Thus, certain factors will be favourable for profitability of certain operations, whilst proving unfavourable for other operations. It is therefore most useful to determine the range of EV's that are associated with economically important traits. Knowledge of these EV's would allow a breeder to evaluate whether a given action would be appropriate around the world or specific to an isolated place. For example, areas having limited access to breeders will have higher EV's for eggs per hen.

Knowledge of the EV's is extremely important in order to concentrate on the relevant traits that will have the largest effect on the profitability of an operation. A suitable selection procedure must then be applied to gain progress in the chosen traits. There are a number of methods available for the identification and selection of the best animals, which can be divided into single and multiple trait selection. Methods representative of each selection strategy are discussed below.

Economically important traits do not involve only the broiler operation; the parent and hatchery operation must also be considered. Determination of these EV's involves evaluation of all production costs and income from each stage. Each stage forms a part of the family tree, where meticulous breeding procedures have been developed to produce a final product broiler boasting superior traits for which it has been selected. Like any family, problems experienced with ancestors are likely to affect offspring. The same occurs in the broiler line: poor performance of parents will affect the performance of broilers and the total number produced. Hence the importance of strict selection procedures and monitoring of numbers required to produce a target number of broilers at the end of the production cycle.

1.2 The Poultry Industry

It is important to consider the factors that make the poultry industry as successful as it is today. The answer lies with the bird itself, due to its ability to adapt and survive in a wide range of environments, supported by its wide genetic diversity, the domestic fowl is now

found throughout the world (Yamada, 1988). Furthermore, the natural fecundity of the hen and the short generation interval allows for rapid growth of selected populations, as well as high selection intensity which translates into rapid genetic progress (Hartmann, 1989).

Apart from poultry being a popular food source, the contribution these birds have made to society is significant. The domestic fowl has been used in nutritional, endocrinological and cancer research benefiting the human race, thus making it a major contributor to scientific discoveries. Furthermore, the fowl was the species of choice with regard to animal genetic studies and a great deal more was known about the inheritance of qualitative traits in chickens than in any other species of domestic animal as a result of the early studies on Mendelian genetics (Hartmann, 1989).

1.2.1 Specialisation of broilers and layers

Prior to the 1950's specialisation within a breed was not practiced by geneticists, thus the males were used for meat production, whilst the hens were kept for eggs. These dual-purpose breeds included White Leghorns, Black Australorps and New Hampshires. But then, as a result of competition between poultry breeders (Strain & Nordskog, 1962b) and the realisation that some strains could be selected for egg production whilst others could be fast growing, specialised egg production and meat-type birds were produced. Laying hens used in the poultry industry today are crosses between the above breeds, whilst broiler breeds are based on Cornish Game and White Plymouth Rock breeds. In all cases geneticists utilise hybrid vigour or heterosis (Appleby *et al.*, 1992) to improve performance in the two specialised strains, which, amongst other benefits, attempts to overcome the negative genetic correlation that exists between egg and meat production.

Genetic selection targets within egg and meat producing lines is totally different. Selection in laying hens is for increased rate of lay, egg weight, earlier sexual maturity and smaller body size, whereas selection in broilers was initially almost entirely for rapid early growth and body conformation, but more recently includes selection for improved feed conversion efficiency (FCE) and resistance to disease. Although the egg and meat industries have diverged, several companies initially had interests in both industries. However, due to the management systems and diseases that are specific to each industry, the market began to split into two separate industries in the 1980's (Hunton & van der Sluis, 2004).

From the onset of this separation both divisions have been confronted with challenges of a different nature. The egg industry was forced to apply complicated selection procedures from the start, due to the inherent low heritability of fertility traits, making it harder to achieve progress.   On the contrary, growth traits possess high heritabilities, thus minimal sophistication of the breeding programmes was required by the meat industry in order to achieve maximum gains (Hunton, 2006). By the 1970's, some broiler breeding companies had still not applied complex pedigree programmes. Evidence of this is in the gains that have been achieved in the meat and table egg industry. Current levels of improvement to egg production are at 1% per year, whereas gains of 2 to 3% are achieved in meat production per year (McKay, 2008), illustrating the competitive advantage of growth traits.

Up until the 1970's the meat industry had not yet experienced any major challenges, but revenge, as it would seem, was sweet. Meat breeders experienced several correlated responses to selection for increased growth rate, which included excessive fat deposition, a range of leg weakness problems and in recent times, ascites (Hunton, 2006). The negative genetic correlation that exists between growth and reproductive traits forced broiler breeders initially to employ management programmes like feed restriction, and thereafter pedigree breeding and selection for reproductive traits, making these programmes just as complex as those applied to egg-type birds.   Genetic selection in the broiler industry has become exceedingly complex as geneticists have had to deal with these issues, as well as those of reproduction, without compromising the performance of the contemporary broiler.

1.3 Progress Achieved

The superlative progress made with broilers over the last few decades can be argued as the pinnacle of all progress studies pursued.   The progress achieved in the modern broiler industry has been influenced by genetic, management and nutritional changes (Havenstein *et al.*, 2003b; Strain & Nordskog, 1962a), as well as in poultry health (McKay, 2008). Data from Havenstein *et al.* (1994) and Havenstein *et al.* (2003b) demonstrate that genetic selection that has been employed by commercial breeding companies is responsible for about 85 to 90% of the increase in broiler body weight that has occurred over the last 45 years. The remaining 10 to 15% is associated with improvements that have been made in nutrition.

Nutrition has and does undoubtedly contribute to the success of the broiler industry, however, whether it has contributed as much as 10-15% to the improvement that has been made in body weight is questionable. Genetic selection is the majority "shareholder" in the progress that has been achieved in broiler body weight. The main contribution of nutrition is to allow the broiler to realise its full potential that has been made possible by the genetic selection it has been exposed to. Since the attributes of the broiler are constantly evolving, the nutrient requirements of the broiler have evolved with the improvements made in genetics (Wiernusz, 2005). Evidence of this lies in the fact that nine revisions of the National Research Council's "Nutrient Requirements of Poultry" have been published (Halley, 2005). Since genetic selection is viewed so highly, it will be discussed with regard to the role it has played in overall broiler improvement. Environmental conditions, or management programmes, will also be discussed since the manifestation of genes will vary in different environments.

Introduction to this topic is best accompanied by an overview of how far the industry has come. A study performed by Havenstein *et al.* (1994) and Havenstein *et al.* (2003b) involving broilers representative of those being grown in 1991 and 2001, illustrated that growth rate increased by nearly 84 grams per year during this 10 year period. To better envisage these improvements, Halley (2005) stated that geneticists are achieving gains in body weight of approximately 0.1% per year, a reduction in FCR of about two points per year and an improvement in breast meat yield of 0.3%, as a percent of live weight, per year. This means that a newly hatched chick increases its body weight by 25% overnight and 5000% to a 2 kg body weight by approximately five weeks (Ao & Choct, 2005). Nicholson (1998) reported a decrease in liveability, mainly due to an increase in the occurrence of disease problems such as ascites and leg disorders, whereas McKay (2008) reported an increase in liveability of 0.22% per year over the last five years.

Havenstein *et al.* (2003b) and Havenstein *et al.* (2003a) conducted a study to compare the performance of the 1957 Athens-Canadian Randombred Control (ACRBC) strain and the 2001 Ross 308 strain of broilers when fed diets representing those from 1957 and 2001. Changes in growth rate, feed conversion (FC) and mortality were the focus of the study by Havenstein *et al.* (2003b), as well as how genetics and nutrition contributed to these changes. The study performed by Havenstein *et al.* (2003a) analysed the changes in broiler carcass characteristics and yield that have occurred between 1957 and 2001.

At 42 and 84 days of age, Ross 308 broilers fed the 2001 diet, reached a body weight 496% and 386%, of that of the ACRBC on the 1957 diet, respectively (Havenstein *et al.*, 2003b). Results show that the body weight of the ACRBC birds increased more on the 2001 diets, than on the 1957 diets. Conclusions drawn from the Havenstein *et al.* (2003b) trial state that genetics, nutrition and other management changes that have occurred over the last 44 years have produced a bird that requires roughly one-third the time (32 vs. 101 d) to reach slaughter weight, and more than a threefold decrease in the amount of feed consumed (estimated FC of 1.47 vs. 4.42) to yield a 1 815 g broiler.

Changes in growth rate are inevitably accompanied by changes in body composition and yield (Havenstein *et al.*, 2003a). Carcass weights of the Ross 308 strain on the 2001 diet were six times heavier than those of the ACRBC on the 1957 diet at 43 days of age. Total breast meat of the Ross 308 broiler on the 2001 diet totalled almost 10 percentage points more than the ACRBC. Whole carcass fat of the Ross 308, on the 2001 diet, averaged 13.7% at 43 days of age, versus 8.5% for the ACRBC on the 1957 diet at the same age. However, at 85 days, the near market age of the ACRBC, the percentage carcass fat was 14.0%, slightly higher than the carcass fat of the Ross 308 at its near market age of 43 days.

The following graphs illustrate the performance levels of FCR and breast meat yield at certain body weights in the year 2004 and 2010. Body weight in 2004 and 2010 is compared at the same age.
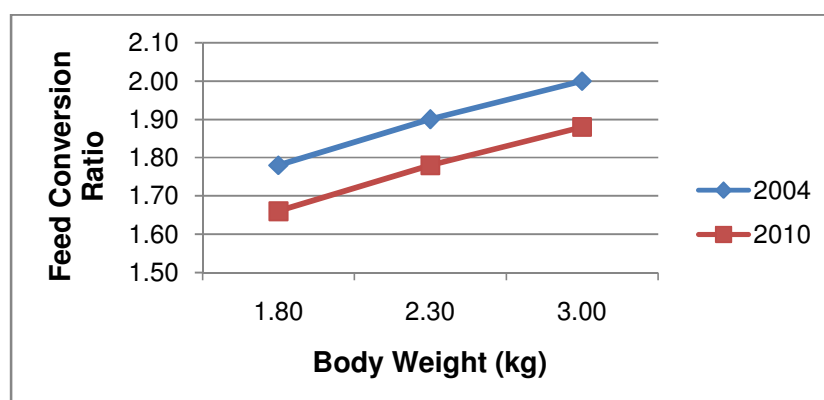
Figure 1.1 Predicted changes in the FCR over a six year period at consecutive body weights (Halley, 2005)
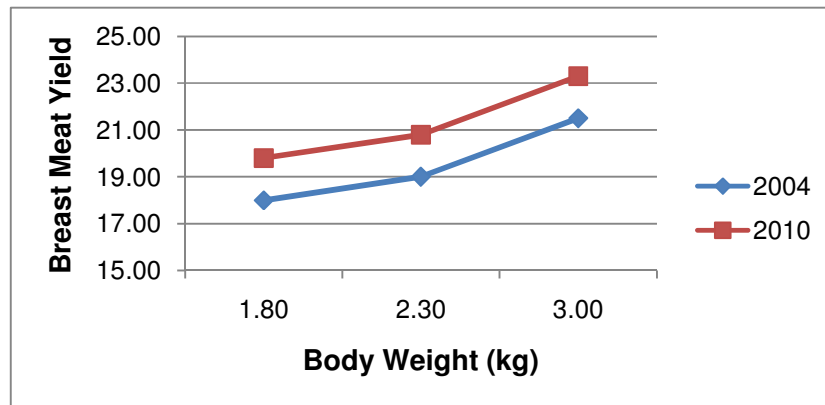
Figure 1.2   Predicted changes in the Breast Meat Yield over a six year period at consecutive body weights (Halley, 2005)
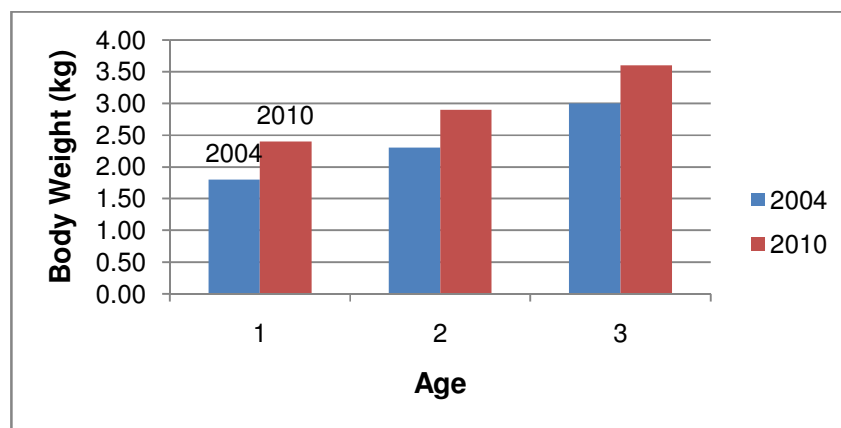
Figure 1.3   Predicted changes in the body weight over a six year period at the same age due to genetic selection (Halley, 2005)

The contribution of broiler production to the meat industry as a whole is illustrated in Figure 1.4.   Evidently the broiler industry is the leading meat producer in the livestock industry. South African chicken consumption, according to the Bureau for Food and Agricultural Policy (BFAP), was 30.5 kg/capita in 2006, and is expected to rise to 34.4 kg/capita in 2014 (BFAP, 2008).   McKay (2008) quoted an annual growth rate of 5% in poultry meat production since 1965.   Poultry meat consumption will continue to escalate each year demanding continuous improvements to the industry.
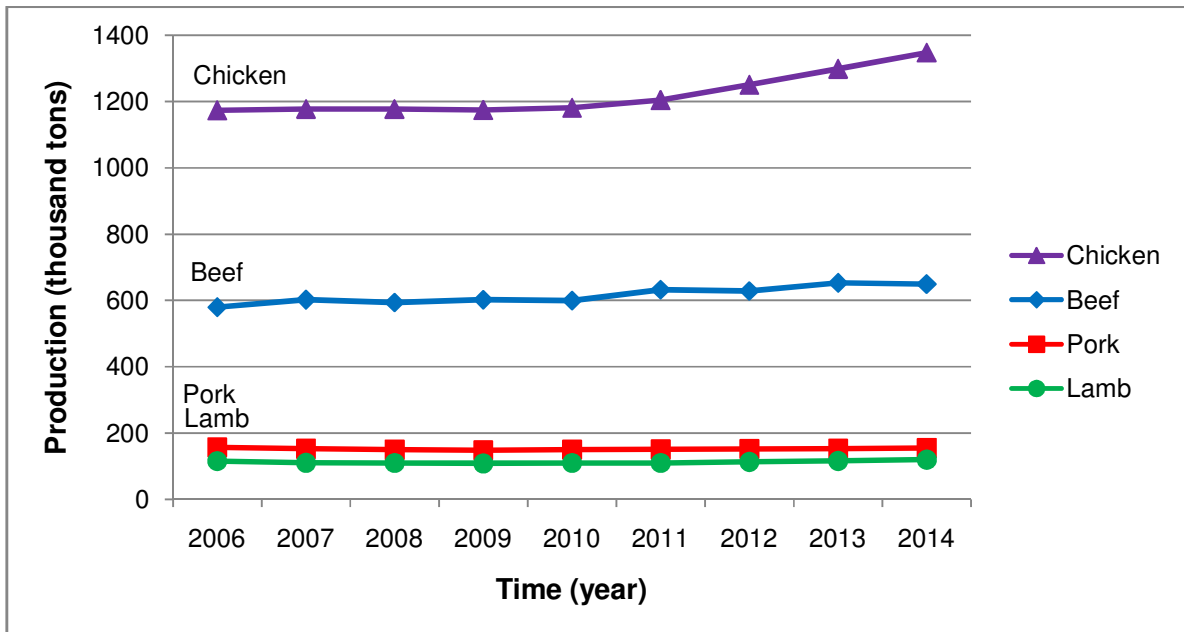
Figure 1.4 Figure adapted from BFAP (2008) illustrating the production levels of chicken, beef, pork and lamb in South Africa for the period 2006 to 2014

The desired effect of the continuous improvements that are made is to decrease production costs or improve profitability. For example, increasing the number of chicks produced per hen may be implemented by improving fertility and hatchability, nutrition of the breeder or genetically increasing the number of eggs that a hen will produce. Reducing the time taken to reach target weight, improving the yield of carcasses and FCE will also result in a reduction of production costs and an increase in profitability. Pasternak & Shalev (1983) developed a model specifically to determine the reduction in feed intake per bird when attaining target body weight a day earlier. They found feed consumption per bird to be reduced by 50 to 60 g. Improvements to these production traits can be achieved by genetic selection for meat yield, growth rate and FCE. Fewer chicks will be required to reach target production scales, feed costs, which make up a large portion of the variable costs, will be reduced or a higher income will result from higher yielding carcasses.

The importance of saving costs and maximising profit in the broiler operation by improvement of broiler and breeder performance is illustrated by the history of economics in the broiler industry. Bodyweight prices per kilogram have remained fairly constant, less than 1% annual change from 1988 to 1998, thus growers have searched for areas where improvements can

be made to maintain their livelihood (Nicholson, 1998). It can also be said that it is the continuous improvements that have allowed poultry meat production costs to remain relatively constant throughout the period from the early 1950's to today (Havenstein *et al.*, 2003b). Reducing mortality in a flock of 50 000 broilers by 1% will generate an extra 1000 kg to sell per crop. Growers need to find novel approaches to improving their income with little extra cost, just an improvement in their management practices. The same responsibility lies on breeder farms, as improvements in the performance of the birds will save costs for the growers due to a shorter growing period or a decrease in feeding costs.

The improvements have mainly been achieved through the growth rate of the broiler progeny, not in the egg laying performance of the parent stock (Strain & Nordskog, 1962a). However, costs in a broiler enterprise are affected by the production potential of broiler progeny, as well as the performance of the parent flock. Thus, knowledge regarding the relative importance of parent and progeny performance as determinants of profitability of a certain strain must be considered when constructing any breeding programme. It is imperative that the cost of production is minimised in order to honour the reputation that poultry meat is a cheaper source of protein, as this is one of the main reasons why it is one of the most popular food resources. It is for this reason that the industry must remain on its toes and at the forefront of research.

1.3.1 Genetics

Most journal articles relating to broilers begin with statistics of milestones that have been achieved through genetic selection. This has undoubtedly contributed to the remarkable performance of the broiler that we witness today. Constant selection of birds with favourable characteristics for the economically important traits will inevitably result in a bird that is suited to the demands of our market. Furthermore, constant updates to our selection techniques and advances made to the technology at our disposal allow us to choose the "best birds for the job" allowing further progress to be achieved.

It is worthwhile taking a look at where poultry genetics started, and how far it has come. Descriptive (qualitative) traits were the main focus of studies in poultry in the early 1900's (Hunton, 2006). Researchers began to consider methods of improving quantitative traits in the 1930's and 1940's, and progress was made even with traits of low heritability such as egg

production and disease resistance. Long-term selection experiments were initiated in the 1950's and 1960's, and the resultant techniques were applied by commercial breeding and development companies that emerged at the same time. From 1960 to about 1980 the literature was occupied with all manner of data relating to studies on poultry genetics but by the 1980's the fascination of the industry with poultry genetics was lost. Molecular genetics replaced the population genetics studies at this time; however, the poultry genome project saw a renewed interest in poultry genetic studies in an academic setting between the 1980's and 1990's.

Chicken gene mapping has also contributed to the success made by geneticists, other than long-term selection trials. Identification of genes or markers influencing traits with a low heritability, or those that cannot be measured on live animals, would be of considerable value to commercial breeders (Hunton, 2003). Complete genome sequencing will be a milestone for poultry genetics as it will aid the discovery of gene functions and facilitate the improvement of traits of economic importance (Romanov et al., 2004). More complex breeding methods must be applied as weight gain is no longer the only significant trait in selection (Hartmann, 1989).

1.3.2 Environment

The phenotype of an animal is subdivided into a portion dependent on its genotype and another on environmental effects (Hartmann, 1990). Reproductive traits have low heritabilities, therefore they are largely influenced by the environment (Hunton, 1990). In order to encourage stocks to perform at, or close to their genetic potential, and maximise profit, broiler producers must attempt to optimise the environment with various management programmes. It must be pointed out that a great deal of the success in commercial broiler breeding operations is due to the control of these non-genetic factors by broiler producers.

Breeders are confronted with a problematical phenomenon known as the genotype-environment interaction. The performance of an individual under one environment may deviate from that under another due to the influence of such interactions (Hartmann, 1990). Therefore, the breeder should attempt to improve the potential performance of the stock for a variety of environments rather than for a specific environment. Alternatively, the breeding company would need to specify the environment (and feed) that would ensure that the strain

reached its potential. Moreover, in the absence of a genotype-environment interaction, the genetic correlation between traits becomes unity.

The early market age of broilers lessens the possibility of genotype-environment interactions from influencing traits such as final weight or carcass quality (Hartmann, 1990). Nonetheless, evidence exists illustrating that body weight gain is not affected much by genotype-environment interactions. These interactions bear more significance with laying hens and broiler breeders, due to the increased length of their production period.

However, it is imperative that the environmental conditions that broilers are exposed to are modified with the continuous improvements being made to their production traits. The modern faster growing, higher yielding broiler responds differently to ambient temperature stress, mainly because heavier birds have less surface area per unit weight for heat dissipation (Wiernusz, 2005). Ventilation of broiler houses should thus receive a great deal of attention to enable the bird to reach its full potential.

Nicholson (1998) stated that the incidence of leg problems, and total mortality, have been reduced under research conditions by manipulation of lighting regimens. Control of photoperiod is especially important for managing reproductive problems that are experienced in broiler breeders. Correct control of the photoperiod can enhance their reproductive performance as was determined by Lewis *et al.* (2003) whom discovered the optimum lighting conditions for broiler breeders.

1.4 Structure of the Broiler Industry

In a non-integrated enterprise the basic production unit is the commercial broiler, and the profit made by the broiler producer is the focus of all decision making (Strain & Nordskog, 1962a, b). On the other hand, in an integrated enterprise, profit potential of the parent flock and the broiler grower must both be considered. The basic production unit for an integrated enterprise is the breeder hen in the hatchery supply flock. In disagreement, Jiang *et al.* (1998) state that the unit of product output for the integrated enterprise is the marketable broiler. Furthermore, the unit product output for a non-integrated enterprise is a broiler egg for the breeder farm, a broiler chick for the broiler hatchery and a marketable broiler for the broiler farm and processing plant. It would be short-sighted to treat the supply flock alone as

the basic production unit, the commercial broiler must also be considered in the equation for an integrated enterprise.

Nevertheless, the aim is to maximise profit in both operations, however, difficulties arise from the negative genetic correlation between growth and reproductive traits, creating a dilemma of whether to place more emphasis on the supply of eggs or the production of broilers. Regardless of the assigned production unit, it is not possible to treat a non-integrated and integrated enterprise in a similar manner. Strain and Nordskog (1962a) confirmed this, as economic weights obtained in their study for an integrated enterprise differed from those for a non-integrated enterprise. Furthermore, Jiang *et al.* (1998) stated that the derivation of EV's will differ between the enterprises.

The broiler industry is an integrated system made up of several contributing players, for example, multipliers, commercial growers and processors (Groen *et al.*, 1998), refer to Figure 1.5.

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        Great Grandparent Stock -   ┌─────────────────────┐
                                    │  GGP Rearing Farm   │
                                    │         ⬇           │
                                    │  GGP Laying Farm    │
                                    └─────────────────────┘   Grandparent Stock Eggs
                                              ⬇
                                    ┌─────────────────────┐
                                    │     GP Hatchery     │
                                    └─────────────────────┘   Grandparent Chicks
                                              ⬇
              Grandparent Stock -   ┌─────────────────────┐
                                    │   GP Rearing Farm   │
                                    │         ⬇           │
                                    │   GP Laying Farm    │
                                    └─────────────────────┘   Breeder Eggs
                                              ⬇
                                    ┌─────────────────────┐
                                    │  Breeder Hatchery   │
                                    └─────────────────────┘   Breeder Chicks
                                              ⬇
                   Parent Stock -   ┌─────────────────────┐
                                    │ Breeder Rearing Farm│
                                    │         ⬇           │
                                    │ Breeder Laying Farm │
                                    └─────────────────────┘   Broiler Eggs
                                              ⬇
                                    ┌─────────────────────┐
                                    │  Broiler Hatchery   │
                                    └─────────────────────┘   Broiler Chicks
                                              ⬇
                  Broiler Stock -   ┌─────────────────────┐
                                    │    Broiler Farm     │
                                    └─────────────────────┘   Broilers at slaughter weight
                                              ⬇
                                    ┌─────────────────────┐
                                    │     Processing      │
                                    └─────────────────────┘   Whole and processed birds
                                              ⬇                ready for sale
                                    ┌─────────────────────┐
                                    │     Consumer        │
                                    └─────────────────────┘
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Figure 1.5   Structure of the broiler industry

1.4.1 Parent Stock

A parent breeder purchases chicks from a grandparent breeder (female chicks are from a crossbred grandparent dam line and male chicks are from a crossbred grandparent sire line) and sells broiler eggs to a broiler hatchery (Groen *et al.*, 1998). The costs involved in a

parent breeder operation include purchasing the female and male chicks, feed, and various variable and fixed costs. Revenue generated by the parent breeder operation consists of income from settable and reject eggs (this amount is dependent on whether it is an integrated or non-integrated enterprise) and income from spent or culled males and females at the end of the production cycle.

At the beginning of the rearing period, the ratio between male and female chicks is set (Groen *et al.*, 1998) usually at about 1:6. A large group of males are introduced into the rearing house so the breeder is able to monitor their behaviour and select the superior males for the laying house. At approximately 22 weeks, the males and females are transferred to the laying house at a ratio of 1:10. The ratio is altered from the rearing to laying house due to the selection pressure that is applied to the males, reducing their numbers. These males, along with any reject females, are sold at the end of the rearing period as culls, and this also generates some income.

Renema & Robinson (2004) aptly described the current position of the parent female , "The modern breeder female is a genetic compromise between two very different selection criteria". She must contain the genes for rapid and efficient growth, whilst exhibiting a high rate of egg production to produce large numbers of healthy chicks at hatching time. The responsibility of the broiler breeder hen is to produce a certain number of offspring, at a satisfactory growth rate, in order to reduce costs, and attain a satisfactory level of fertility in order to reduce their own numbers thereby reducing feed costs again. Consequently, a good selection programme is necessary to ensure optimum performance of these birds. However, poor egg production, fertility and hatchability are some reproductive problems experienced in breeds used for meat production (Chambers, 1990).

1.4.2 Broiler Hatchery

Eggs from the breeder flock are hatched at the hatchery to become final product broiler chicks (Groen *et al.*, 1998). Revenue from the broiler hatchery is derived from selling day-old broiler chicks, either A-grades or downgrades, and reject eggs. A portion of the broiler eggs set in the incubator will not be fertile and a portion of the eggs set that are fertile will not produce living broiler chicks (determined by the percent hatchability of fertile eggs). Commercial broiler hatcheries generally make use of multi-stage incubators; broiler eggs are

introduced into a common incubator twice per week, whereas single-stage incubators are commonly used in great-grandparent, grandparent and parent hatcheries where the eggs are of significantly more value (B. Edmondson, 2007, Pers. Comm.[2]). All eggs are placed in the incubator at the same time, minimising the risk of new eggs entering and spreading bacteria to the current eggs, thereby maintaining high hygiene standards. Furthermore, single-stage incubators allow for more specific breed and flock incubation resulting in more reliable production records.

1.4.3 Broiler Farm

Broiler chicks are purchased from the hatchery by the broiler farm at a uniform price per chick (Groen *et al.*, 1998). The sex ratio of female:male chicks is assumed to be 1:1. The bulk of the revenue from a broiler farm is from the sale of broilers at a target body weight. Payment is based on the final weight of the bird. The length of the growing period is determined by the target weight which is set by the market (consumer). The growth rate achieved by the birds can alter this growing period, hence the interest in this trait, since an improvement in growth rate can shorten the growing period, thereby reducing production costs. An optimum slaughter age does exist and must be considered (Dyfri Jones, 1962). It is at the point where marginal costs equal the market value of the bird; each additional unit of weight over and above this point cause the marginal costs to escalate and result in a loss. The main deciding factors for the most suitable slaughter age are the feed price, having the largest influence on the marginal costs, and the broiler market price. At a fixed broiler market price, the higher the feed price, the lower the optimum slaughter age, and at a fixed feed price, the higher the broiler market price the later is the optimum slaughter age. The weight acceptable to the consumer bears a lot of importance and must also be taken into account.

1.4.4 Processing

The processor releases a range of products to the consumer market. These include the whole bird, individually quick-frozen (IQF) products, fresh portions (breast, wing and leg), deboned breast and value-added products (chicken steaklets etc.). The latter three fall under the category of further processed products. Quality of the product is the main factor influencing the price fetched by a particular product. Quality is negatively affected by

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[2] B. Edmondson, Keystone Hatchery, P.O. Box 121, Dargle, 3265

scratches, bruises and general damage of the carcass, resulting in downgrading of the whole carcass. Once a carcass has been damaged, it will not undergo further processing as this procedure is costly and the damaged portion would fetch a lower price.

Quality of the whole bird is classified as the percentage of the carcass in grade A (Groen *et al.*, 1998; Jiang *et al.*, 1998). Quality of the portions is defined by the relative dressing percentages for the breast, wings and legs. Percentage white meat and percentage dark meat is often used to represent the yield of breast, wings and legs. Breast and wings are defined as white meat, whilst legs are defined as dark meat.

1.4.5   Breeding plans used in the production of commercial broiler chickens

The momentous success of the broiler industry did not occur overnight. It took careful planning and research into the requirements of the broiler. Breeding received particular attention as it is a means to producing a bird suited to the requirements of the breeder. Each major broiler company will have its own unique breeding process used for producing commercial day-old chickens, but the basics remain the same. Broilers are the great grandchildren to a pedigree of superior genetics. Each of four great grandparent (GGP) lines have been carefully selected for suitable economically important traits and are crossed to maximise the benefits of hybrid vigour.

Hybrid vigour, or heterosis, was identified as the easy route to improvement, particularly in traits with low heritability where progress is not as easy to achieve (Hunton, 2006; Pollock, 1999). The highly efficient poultry industry owes it's success to the extensive use of heterosis or hybrid vigour in both laying and broiler strains (van Tijen, 1977). Parent stock were initially sold by commercial breeders yielding two-way cross progeny (Cornish Game x White Plymouth Rock), although on the rare occasion some breeders may have worked with three-way and even four-way crosses (Hunton, 2006). However, as the expected performance level was raised and superior performance of parents became a concern, so more three-way and four-way crosses were introduced.

Pure breeding within strains or breeds makes use of the additive effects of genes (van Tijen, 1977). Conversely, hybridisation utilises the non-additive effects of genes (dominance and epistasis). The result of the non-additive effects is that the performance of the progeny

cannot be predicted from the parent generation. Therefore the possibility for vast improvement of the progeny is possible, however, on the contrary, the performance of the progeny could be below that of the parents. Thus the cross progeny must be tested. This method also alleviates the problems associated with inbreeding. Heterosis is maximised when the two parent lines are largely homozygous, having considerably different gene frequencies.

Crossbreeding is utilised extensively in the broiler industry. Parent stock themselves stem from crossbreeding, which has been estimated to improve hatching eggs of the Perdue breeder female by 15% (Pollock, 1999). Broilers capitalise on the benefits from crossbreeding as they share 50% of their genetic background with each parent stock line (Groen *et al.*, 1998), producing a bird that has superior growth rate and egg production. Figure 1.6 below, illustrates the crossbreeding that occurs in the breeding hierarchy of the broiler industry. Pure line GGP stock is imported into South Africa as day old chicks (D. Bone, 2007, Pers. Comm.[3]). For the male lines, there will be males and females present for line "A", as well as for line "B". Additionally, for the female lines, there are males and females present for line "C", as well as for line "D". Male lines contribute traits like growth rate, edible meat yield and FCE, while the females contribute traits like conformation, edible meat yield, egg production, and in some cases, FCE (Pollock, 1999). Uniting of male and female stocks will result in a beneficial combination of productive and reproductive traits.

Selection for reproductive and productive traits can be effected in two ways (Pollock, 1999). The most economically significant traits are improved by positive selection which is of a high intensity and involves selecting from among the best families. Improvements to the minor traits, including fertility, hatchability, egg production and liveability are achieved by removing the poorer performing families and this is known as a low intensity method. This is to ensure that a level of performance is maintained in the minor traits, whilst improvements to the major traits accumulate.

At GGP level, particularly for the two male lines, the first of two selections is performed at the expected slaughter age that the final producer of the broiler is aiming for (D. Bone, 2007, Pers. Comm.[3]). The major traits that the birds from each line are primarily selected for are as follows: Selectors of line "A" will focus on growth rate, FC, leg length (this trait is particularly

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[3] D. Bone, 033 2666199, P.O. Box 460, Hilton, 3245

important in the male of the male lines), liveability, conformation (this trait is particularly important in the female of the male lines) and any general physical defects. The selectors of line "B" will focus on the same traits as in line "A", excepting leg length. The "C" line selectors concentrate on the same traits as line "A", taking special note of leg length as this trait is very important in what will become the male of the female line. The selectors of line "D" focus on any general physical defects and liveability.

A second selection performed at both GGP and grandparent (GP) levels is done at 20 weeks of age (D. Bone, 2007, Pers. Comm.[3]). This selection is on a relatively "small" scale to ensure that only the best birds are kept for breeding purposes. The selection of the males, in both the male and female lines, is particularly important to ensure well-developed, strong and long legs. The selection pressure for the first selection of the different lines is of major importance and varies from breeder to breeder as it is dependent on the objectives of the breeder. At parent stock (F1) level, the primary breeder must focus on the reproductive traits of the female line, both with production and hatchability.

Although the general traits that each line is selected for are predetermined, the breeder must consider updating their breeding programme at regular intervals. It is not feasible for a breeder to select birds based on specific marketing and cost situations; focus should rather be placed on breeding for all conditions, or similarly, the average conditions expected in the future (Harris, 1970). Thus the importance of economic studies and economic forecasting so that the necessary adjustments can be made to breeding programmes to yield a bird that is suitable for the future market. It must be noted that decisions made today will only come into effect when the broiler chicks hatch approximately four years later.

The breeding structure for the South African broiler industry is as follows: Line "A" males are crossed with line "A" females, line "B" males are crossed with line "B" females, line "C" males are crossed with line "C" females and line "D" males are crossed with line "D" females, the result being GP males and females of lines "A", "B", "C" and "D" (D. Bone, 2007, Pers. Comm.[3]). The females from line "A" and "C", and the males from line "B" and "D" are culled as they are no longer valuable to the breeding programme. These culled birds are however not sold, as the producer has an agreement with the supplier not to release these birds to the public as they remain valuable birds with respect to their breeding potential, although they are

no longer required in the breeding programme. Thus, males from line "A" are crossed with females from line "B", and males from line "C" are crossed with females from line "D".

The result being parent males and females of lines "AB" and "CD" (D. Bone, 2007, Pers. Comm.[3]). Females from line "AB" and males from line "CD" no longer offer any value to the breeding programme and are sent to the broiler hatchery to be sold as broilers. Since they are not as genetically superior as the broilers, they are sold for approximately 20% less than the full price for a day-old broiler chick. Males from line "AB" are then mated to females from line "CD", resulting in broiler males and females of line ABCD.
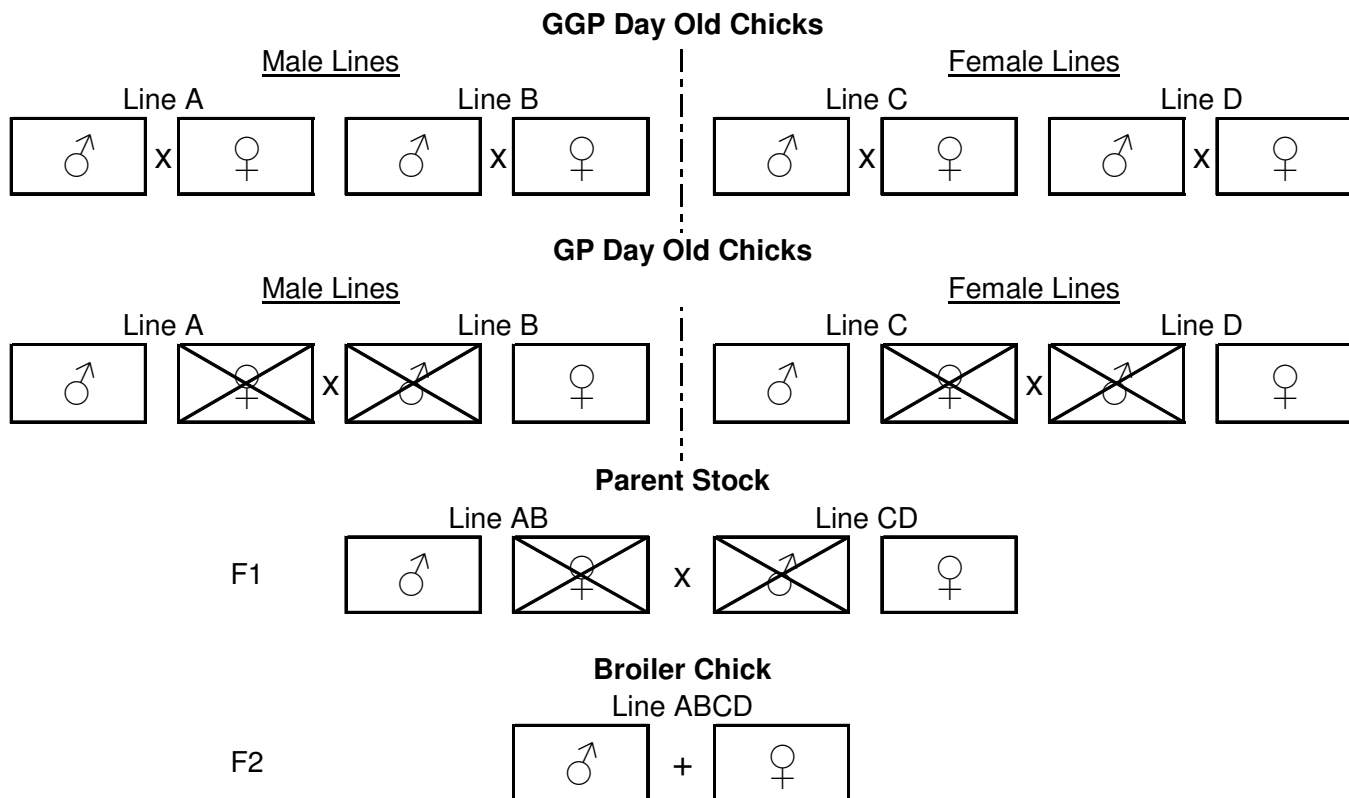
Figure 1.6   Breeding structure of the South African broiler industry (D. Bone, 2007, Pers. Comm.[3])

1.4.6 System Scaling

Each operation has targets of total broilers that they aim to produce annually, these targets being based on the operations' market share (B. Hundley, 2007, Pers. Comm.[4]) and the expected consumer demand (Groen *et al.*, 1998). There is a process involved in determining the number of parent stock, GP stock and GGP stock required to achieve the target number of broilers (B. Hundley, 2007, Pers. Comm.[4]). A series of complex, reverse calculations need to be performed accounting for production levels at each stage of the cycle. For example, egg production, fertility, hatchability and mortality rate of the breeding stock, and live weight, carcass yield and early and late mortality of the broiler progeny must be considered (Groen *et al.*, 1998). A company with a target of one million broilers requires comparatively fewer parent stock, and successively fewer GP and GGP stock in order to produce the one million broilers. This is illustrated by Figure 1.7. The same cannot be said for the value of the birds, as each climb up the pyramid can represent a ten-fold increase in its value (B. Edmondson, 2007, Pers. Comm.[1]).
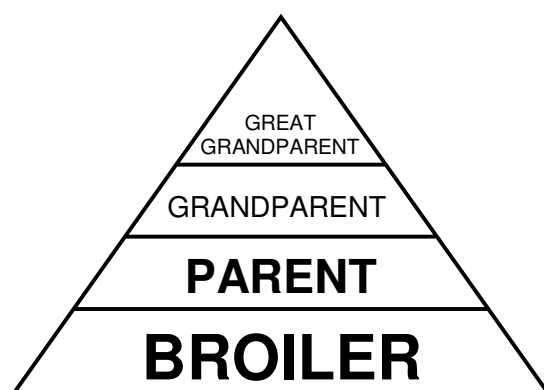
Figure 1.7 Pyramid demonstrating the relative quantities required in order to produce the target number of broilers

Table 1.2 illustrates the production levels required to satisfy a given target. If an operation were required to produce 1 000 000 kg of whole birds per cycle, the final body weight, whole bird dressing percentage, and dead on arrivals at the processing plant would need to be known in order to calculate the number of finished broilers required. In order to calculate the number of broiler chicks required, the total culls and mortalities for the broiler growing period

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[4] B. Hundley, Pet Food Industry, P.O. Box 1027, Hilton, 3245

must be known. In order to calculate the number of broiler eggs required, the total reject, fertile and hatchability of fertile eggs must be known, as well as the total downgrades. Calculation of the number of breeder males and females requires information regarding the number of settable eggs per hen, the total mortalities and culls over the laying period for both males and females and the male to female ratio for the laying period. Information required in calculating the number of parent female and male chicks includes mortalities, culls and sex errors during the rearing period.

Table 1.2   The number of birds required (up to and including parent chicks) in the production cycle to produce 1 000 000 kg of whole broilers per cycle under normal circumstances, and a 20% increase and decrease in body weight and settable egg number

Production Scale	No. Required	Body Weight[1]		Settable Eggs[2]	
		-20%	+20%	-20%	+20%
# Parent Female Chicks	7 493	9 366	6 244	9 382	6 237
# Parent Females Housed	7 225	9 031	6 021	9 046	6 014
# Parent Male Chicks	1 041	1 301	867	1 303	866
# Parent Breeder Males	819	1 024	683	1 026	682
# Broiler Eggs	917 760	1 147 200	764 800	917 760	917 760
# Broiler Chicks	720 943	901 178	600 786	720 943	720 943
# Broilers Finished	680 135	850 168	566 779	680 135	680 135

[1]Body Weight is the final body weight of the broiler at the end of the growing period

[2]Settable eggs is the number of settable eggs produced per breeder hen per cycle

To illustrate a few of the problems that a breeder would be confronted with; if more broilers are required, but superior breeding stock is lacking, the selection pressure on the breeding stock could be reduced, however, breeding stock of average value would be included, resulting in a phenotype that is below standard for the broilers (B. Hundley, 2007, Pers. Comm.[4]). A breeder must also take into consideration that not all breeding stock has the same characteristics. For example, the "D" females from the grandparent line have been bred for improved meat traits, whilst the reproductive traits of the "B" females have received more attention. Thus, the reproductive traits of the "D" females would be inferior, hence more "D" females would be required in order to produce the same number of eggs as the "B" females.

An improvement in the production traits of the breeding stock will result in a reduced number of breeding stock required to produce the target number of broilers, resulting in decreased production costs (B. Hundley, 2007, Pers. Comm.[4]). Similarly, an improvement in broiler traits will benefit the operation, as reduced mortalities and increased body weight translate to fewer broilers being required to meet the target number, which results in lower production costs. Hence, both broiler and breeder traits are important when evaluating the profitability of an operation. Thus, a compromise must be reached as to which traits should receive more emphasis in a breeding programme, and this would depend on their relative influence to the profitability of an operation.

Broiler body weight influences the production scales (or number of birds required to reach target production levels) of broiler producers, whereas hatching egg number has no effect (Groen *et al.*, 1998), refer to Table 1.2. However, both hatching egg number and broiler body weight influence the production scales for parent stock breeders. An improvement made to both broiler growth rate and egg production of the parent stock has the same effect on production scale of the parent breeder. When referring to the costs and profits made by the broiler producer and processor, these are directly influenced by a change in body weight. While the costs and profits of the parent stock breeder and hatchery are only indirectly affected by a change in body weight of the broilers. A result of an increase in body weight of the broilers is a reduction in the number of broiler eggs required upstream.

1.4.7 Modelling and Simulation Modelling

There are constant advances in the techniques used for research of poultry. Among the most important developments is modelling. Modelling has demonstrated its value to poultry scientists as it can be used to identify the economic consequences of management decisions and/or market changes (Zoons *et al.*, 1991) and can account for all variables (Gous *et al.*, 2006). This is a very powerful tool as "plans of action" can be evaluated before they are implemented to determine whether they will be beneficial to the operation or not. This could save a lot of time, money and effort, as focus will only be placed on projects that are worthwhile and profitable.

Several models have been developed to analyse the economics of various operations within the broiler industry. Strain and Nordskog (1962a) developed a model to assess profit

potential of the parent flock and broiler progeny in an integrated and non-integrated enterprise. Performance traits of both the parent flock and the broiler progeny were considered. (Moav & Moav, 1966) were the first to propose the use of profit equations, integrating the cost and income of a production system. Part of their study was developing profit graphs describing net profit per unit weight of broiler meat, related to market age and the total number of eggs per hen in the parent stock. Groen *et al.* (1998) developed a deterministic model for the economic evaluation of broiler production, and the derivation of EV's in integrated and non-integrated broiler breeding systems. Pasternak *et al.* (1986) and Shalev & Pasternak (1983) estimated the relative GEV's of all traits influencing the profitability of a turkey and broiler enterprise respectively, by estimation of production costs per unit of market live weight.

Simulation models can also be used to demonstrate selection strategies. Muir's (1997) definition states "Simulations are based on a set of assumptions from which data is generated and alternative breeding schemes are compared". However, in the past very few simulations have been performed using a broiler population. Simulation modelling is pivotal in artificial selection, as it will demonstrate the relative efficiencies of selection strategies and will not have to be conducted over the many years that such a project would normally take to complete if live birds were being used. The value of such simulation models is demonstrated in this study.

1.5 Processes involved in genetic selection

Breeding programmes used to improve certain traits employ artificial as opposed to natural selection, which means that selection is applied by the geneticist. Selection can simply be defined as allowing some animals to be parents of the next generation, while depriving others of the privilege (Dalton, 1981). Selection operates by changing the frequency of genes, or combinations of genes, that occur in a population. Therefore, the "newly improved" population would have a higher frequency of favourable genes according to the breeder, and a lower frequency of less favourable genes compared with the base population.

1.5.1 Genetic factors to be considered in breeding programmes

There are three important aspects that affect the response of traits to selection and need to be taken into consideration when formulating breeding programmes. These include the heritability of a trait, the genetic correlations between traits and the relative economic importance of a trait (Gowe & Fairfull, 1995). Other considerations are the selection intensity, the selection differential and the generation interval.

1.5.1.1 Heritability

This is the term used to describe the strength of inheritance of a character, whether it is likely to be passed on to the next generation or not (Dalton, 1981). The most important function of heritability in the genetic study of metric characters is its predictive role, expressing the reliability of the phenotypic value as a guide to the breeding value (Falconer & Mackay, 1996). Only the phenotypic values of individuals can be measured directly, but it is the breeding value that determines their influence on the next generation. Therefore, if a breeder selects parents according to their phenotypic values, the success in changing the characteristics of the population can only be predicted from a knowledge of the degree of correspondence between phenotypic values and breeding values, the heritability.

A heritability value of between 0 and 0.1 is considered low or weak, while a value between 0.1 and 0.3 is medium or intermediate (Dalton, 1981). A value of 0.3 or above is considered high or strong, and a trait with this heritability value is considered highly heritable. Selection will be more effective, and more progress will be made, if the heritability is higher (Gowe & Fairfull, 1995). Variable conditions will reduce heritability, whereas this will increase under more uniform conditions (Falconer & Mackay, 1996).

It is generally concluded that characters with the lowest heritabilities are those most closely connected with reproductive fitness, while the characters with the highest heritabilities are those that are considered to be the least important as determinants of natural fitness (Falconer & Mackay, 1996). The remarkable progress that has been achieved in meat production has been partly due to the high heritability of most meat production traits (0.5 or higher). Heritability estimates of various economically important traits are given in Table 1.3.

Table 1.3   Heritability estimates of a number of important production traits from various sources

Trait	Heritability	Reference
Mature body weight	0.56	(Kinney *et al.*, 1969)
	0.25-0.65	(Dalton, 1981)
	0.49	(Marks, 1985)
	0.56	(Manson, 1972)
	0.46	(Kinney & Shoffner, 1965)
Age at first egg (AFE)	0.42	(Kinney *et al.*, 1969)
	0.15-0.30	(Dalton, 1981)
	0.42	(Manson, 1972)
	0.41	(Gowe & Fairfull, 1995)
	0.39	(Marks, 1985)
	0.34	(Kinney & Shoffner, 1965)
	0.32	(Kinney, 1969)
Annual egg production Rate (%) of production	0.31	(Kinney *et al.*, 1969)
Egg production	0.15	(Kinney & Shoffner, 1965)
Egg production (%)	0.15	(Marks, 1985)
Hen housed egg production (from AFE to 500 days)	0.05-0.1	(Dalton, 1981)
Egg weight	0.45	(Kinney *et al.*, 1969)
	0.49	(Manson, 1972)
	0.52	(Gowe & Fairfull, 1995)
	0.57	(Marks, 1985)
Fertility	0.0-0.05	(Dalton, 1981)
Hatchability	0.1-0.15	(Dalton, 1981)
Viability	0.01-0.15	(Dalton, 1981)
Shank length	0.4-0.55	(Dalton, 1981)
Body depth	0.2-0.53	(Dalton, 1981)
Breast width and angle	0.15-0.35	(Dalton, 1981)
Feed efficiency	0.16	(Manson, 1972)

1.5.1.2 Genetic Correlation

The genetic cause of correlations between traits is mainly pleiotropy (where a gene affects two or more traits), although linkage may also result in correlated traits (Falconer & Mackay, 1996). When selective pressure is applied to one trait, genetic change is effected in that particular trait, as well as in other traits that are genetically correlated with it (Strain & Nordskog, 1962a). The magnitude and sign of the genetic correlation will determine whether this correlated response is favourable or unfavourable. Thus, any genetic change that is implemented may influence profit potential.

When selection is applied to a particular trait, it is necessary to calculate the direct response to selection in that particular trait, and the correlated response to selection in the remaining relevant traits. The magnitude of the genetic correlations between traits governs the selection pressure that is applied to each trait. The optimum level for each trait must be determined based on the influence that particular trait has on an economically important trait. Orozco (1979) and Hogsett & Nordskog (1958) stated a noteworthy point; traits possessing a zero correlation between them, or even a positive one, will display a negative correlation after the onset of the selection process. Hogsett & Nordskog (1958) further explained focusing on egg production and egg weight. Selection is expected to change the frequency of genes having similar effects on the traits near to zero or one. Consequently, the majority of the remaining genetic covariance will be due to genes affecting the traits in opposite directions. The authors believe that the negative genetic correlation existing between egg production and egg weight is due to the selection that has been applied to the improvement of both of these traits prior to 1958. Furthermore, they believe that the negative genetic correlation between egg production and body weight may be due to the positive association between body weight and egg weight. Thus, breeders cannot escape the effects of genetic correlations and must consider them in every breeding programme. An attempt made by breeders to overcome these hurdles is by using specialised sire and dam lines for broiler production, in order to minimise the effects of these negative relationships (Chambers, 1990).

Correlations in the chicken between early body weight and age at first egg, egg production and fertility were found to be negative, whereas correlations between early growth rate and adult body weight and egg weight were positive (Marks, 1985). Kinney *et al.* (1970) found varying responses in age at sexual maturity, egg weight and body weight as correlated

responses to selection for short term rate of egg production using four different selection strategies. The four selection strategies included individual, sire family, dam family and index selection. Most techniques displayed correlations in the same direction as discussed above, although some demonstrated a stronger correlation than others. Thus, it may be possible to employ a certain technique in order to minimise the unfavourable correlations.

Chambers (1990), however, argues that these values are too small to have a significant effect on the simultaneous genetic improvement of these traits. Although true, this will only apply for the first few generations of selection, thereafter the correlations significantly hinder further progress in all traits, mostly due to the depletion of individuals displaying superiority for the negatively correlated traits. Table 1.4 below, illustrates the genetic and phenotypic correlations that exist between some of the economically important traits. The phenotypic correlations were used for calculation of the GEV's and were taken as an average, of the below values, obtained from the literature.

Table 1.4   Genetic (above) and phenotypic (below) correlations existing between some of the economically important traits in the broiler industry

	Mature body weight	AFE	Egg weight	Egg production/Hen day production	Viability
Mature body weight		0.06 / 0.06 / 0.4	0.33 / 0.36 / 0.25	-0.55 / -0.44 / -0.1	0
AFE	0.12 / -0.2		0.07 / 0.1 / 0.4	-0.11 / -0.34 / -0.4	0.7
Egg weight	0.23 / 0.3 / 0.35	-0.01 / 0.2		-0.2 / -0.05 / -0.5	-0.2
Egg production/Hen day production	-0.04 / -0.1 / -0.03	0.01 / -0.3	0.02 / 0.2 / -0.14		0.4

References: **(Marks, 1985)**   **(Dalton, 1981)** – (Hen day production)
            (Kinney, 1969)   **(Hogsett & Nordskog, 1958)**

Given that feed costs constitute about 70% of the total cost of broiler production (Zhang & Aggrey, 2003) it is worth examining the effect of various factors on the variation in income over feed costs. Such an exercise was conducted by Strain & Nordskog (1962b) who showed that eight week body weight accounted for the largest proportion of the total variation, followed closely by eight week FC. Broiler liveability and number of hatching eggs trailed far behind, nonetheless accounting for a small part of the total variation in income over feed costs. The amount of total variation accounted for by hen-housed egg production was negligible when considered alone. However, when considered in combination with broiler body weight, together they accounted for the largest percent variation compared to alternate combinations. This result is due to the importance of the genetic correlation between egg production and body weight.

1.5.1.3 Economic value

When constructing a breeding programme, it is important to consider the genetic economic relationship between traits (Harris, 1970; Strain & Nordskog, 1962a). The EV of a trait represents the ability of that trait to improve economic efficiency of an operation, when an improvement is made to the genetic merit of the trait in question (Groen, 1988; Groen *et al.*, 1998; Hazel, 1943). The economic weight of a trait can be calculated by determining the expected change in profit potential, or cost price (Groen *et al.*, 1998), corresponding to a one unit change in the trait (Groen, 1988; Hazel, 1943; Strain & Nordskog, 1962a). EV's can also be calculated by performing sensitivity analyses at varying production levels of traits. The value obtained for the economic weights is decisive in the direction and amount of progress that is achieved with the selection index (Smith, 1983). In order to determine the GEV's of each trait, the genetic gains expected annually and EV's must be considered together (Pasternak *et al.*, 1986). Traits with the highest economic importance should be given preference when deciding which traits to use in a selection programme (Jiang *et al.*, 1998). A small genetic gain in a trait of high EV is more desirable than a large genetic gain in a trait of little EV (Gowe & Fairfull, 1995). Traits considered to affect profitability include growth rate, food utilisation, fat content, egg production, fertility, hatchability, and mortality (Pasternak *et al.*, 1986).

Economic weights are not solely dependent on the ability of the trait to improve the economic situation of an operation, but also the level of performance of the breeding flock (Hogsett &

Nordskog, 1958). The EV's obtained by Pasternak *et al.* (1986) illustrate the trends exhibited based on the relationship between traits and changes in performance. For example, as egg production is increased, the hatching egg cost is reduced. However, the value of an additional hatching egg is decreased, as well as the value of an additional 1% fertility or hatchability. Since egg production is improving in this case, enhanced fertility or hatchability loses its value, or importance, as part of a breeding programme. When egg production of turkey hens was poor, fertility and hatchability had a higher relative EV than other traits such as broiler turkey mortality, food utilisation and eviscerated yield due to the positive correlation of these traits with egg production. More emphasis would be placed on these traits since improving their value would indirectly improve the egg production of turkey hens.

Additionally, as the number of hatching eggs per dam increases, the relative EV of improvements in growth-related traits increases, whereas the converse is true for the value of selection for egg production (Pasternak *et al.*, 1986; Shalev & Pasternak, 1983). This is because a genetic improvement achieved in fecundity can reduce the dam's production costs, while a genetic improvement in turkey growth rate and food utilisation will be multiplied by the offspring of each dam. Therefore, the advantage of the offspring traits increases as the number of offspring per hen increases. From this angle EV calculation can be seen as the calculation of the optimum balance between traits to achieve the most profit.

Shalev & Pasternak (1983) provided workable examples demonstrating the worth of certain traits. The authors stated that at 130 hatching eggs per hen housed, the EV of a genetic improvement of 20 hatching eggs is equivalent to a genetic improvement of 13.1% in hatchability, or a 4.6% reduction in broiler mortality, or a 3.3% improvement in food utilisation, or a 1.9% increase in eviscerated carcass yield, or reaching target weight 1.5 days earlier or a 77g increase in live body weight. Although the parallels drawn here may not currently reign true, the economic equivalence of 20 hatching eggs to the other economically important traits is noteworthy.

EV's are not constant and can vary from breed to breed, or region to region, even within the same breed (Hazel, 1943). Fluctuations in heritability estimates of traits may also cause the relative EV of traits to vary (Pasternak *et al.*, 1986). However, these variations may only have a minor influence on the relative importance of these traits. The GEV may even change while a breeding programme is in progress (Hazel, 1943), as the phenotypic value of the trait is

altered by selection (Gowe & Fairfull, 1995), or if market demands and economic conditions change (Gowe & Fairfull, 1995; Hazel, 1943). This is well illustrated by the selection for breast meat yield, which was regarded previously as relatively unimportant. However, it is currently the most valuable part of the broiler, and selection for increased breast meat yield has become essential in any selection programme for broilers. This transition from "normal" broiler strains to so-called meat-type or high yield broilers of today, has resulted in a doubling of the percentage yield of breast meat, mainly during the past 10 years (Havenstein *et al.*, 2003a). Thus it is vital that geneticists constantly assess the possible production problems and customer comments, and in doing so make the appropriate changes to their selection strategies. Research has however shown that frequent adjustment of the EV's, due to minor changes in market share or the performance of the stocks, is unnecessary as the changes made to the selection index are negligible (Smith, 1983).

1.5.1.4 Genetic Gain

Genetic gain is controlled by three important factors, namely heritability, the selection differential and the generation interval (Dalton, 1981). Genetic progress is measured as the response to selection, and is the difference between the mean phenotypic value of the offspring of the selected parents and that of the whole of the parental generation before selection (Falconer & Mackay, 1996). The rate of progress that is made in improving a trait is directly related to its heritability. The higher the heritability of the trait, the more progress that will be achieved.

The selection differential is the superiority of the selected parents over the mean of the population from which they came (Dalton, 1981). If the variation in the selected population is very low, then the selection differential will be reduced as the animals will not be significantly different from one another. The intensity of selection can be calculated from the selection differential and the phenotypic standard deviation. Selection intensity is the proportion of the population that has been selected as parents for the next generation (Hunton, 1990). The generation interval is the time-interval between generations, and can be defined as the average age of the parents when their offspring are born (or hatched) (Dalton, 1981). The average generation interval of the chicken is much lower than other livestock, thereby allowing for rapid progress. A broiler female will reach sexual maturity not earlier than 18 weeks of age, but would need approximately 10 additional weeks to reach peak production

(28 weeks). The egg has to be hatched, taking approximately three weeks, before the next chick starts out in life. The generation interval is thus about 32 to 35 weeks, far below that of other livestock.

A combination of three factors must be considered when determining what emphasis to place on traits in a selection programme (Harris, 1970). These factors include the economic importance of each of the traits, the potential for genetic improvement in each of the traits, and the genetic correlations between the traits. Inclusion, or exclusion, of a trait from a selection programme depends on the surplus value of the economic improvement relative to the cost incurred in making the improvement.

Once the particular trait has been decided upon, the next challenge is selecting suitable individuals to improve the level of the trait in future generations. Animals differ in breeding value, similarly to phenotype, for each of the traits (Hazel, 1943). The total value of an animal is the summation of its several genotypes, each genotype being weighted corresponding to the relative EV of that trait. An animal's genotype for a trait may be defined as the sum of the average effects (strictly additive) of its genes that influence the given trait. Smith (1936) discussed the difficulties facing plant breeders, nevertheless, parallels can be drawn to poultry breeding: quantitative traits are those traits that breeders are primarily concerned with. They present a challenge as genotypic values of individuals or families are not simply determined since heritable variations are concealed by larger non-heritable variations. The phenotypic value of an animal, which can be simply observed, does not accurately represent the genotypic value due to the non-heritable variations (Smith, 1936), such as environmental factors, dominance and epistasis (Hazel, 1943). Thus, various tests and trial selection programmes must be performed in order to determine the genotypic value and select the superior individuals.

1.5.2 Selection Strategies

Several methods of selection exist, but they are not equally efficient (Hazel & Lush, 1943). The most efficient method is defined as one resulting in the maximum genetic improvement per unit of time and effort made. The principal methods of selection that exist are individual or mass selection, family selection, within family selection, family-index or combined selection and multiple trait or index selection (Falconer & Mackay, 1996). Individual selection, between

family selection, within family selection and family-index selection are selection techniques selecting for one trait at a time (Lynch & Walsh, 2000). Broiler geneticists would have to decide whether to select for increased growth rate or egg production when using one of these selection programmes. Furthermore, the genetic correlations existing between traits complicate single trait selection, creating a need for inclusion of more than one trait in a selection procedure; under these conditions it is advisable to implement multiple trait selection or index selection (Falconer & Mackay, 1996). These selection techniques and their practical applications will be discussed below.

1.5.2.1 Single Trait Selection

1.5.2.1.1 Individual Selection

Individual selection, otherwise known as mass selection, is defined by Falconer & Mackay (1996) as a process whereby "Individuals are selected solely in accordance with their own phenotypic values". This method should be employed if there is no limit to its use since it is the simplest to perform, and in most cases will produce the most rapid response (Falconer & Mackay, 1996).

1.5.2.1.2 Family-based selection

Under some circumstances individual selection may not be practically applied due to a difficulty in determining certain traits of individuals. Here, family-based designs become useful since they allow for greater accuracy in predicting an individual's breeding value (Lynch & Walsh, 2000). This breeding value is obtained from information from the relatives. An example of the application of a family-based design is the egg production of broiler breeders. This trait cannot be measured in the broiler males, hence their breeding values are estimated using information from their female relatives.

Family-based designs can be constructed in one of two ways; the first being the difference between family means, and the second the difference between individuals within a family. Family-based selection is further divided into three main techniques; namely between family selection, within family selection and family-index selection.

1.5.2.1.3 Between Family Selection

Falconer & Mackay (1996) define between family selection as the method whereby "Whole families are selected or rejected as units, according to the mean phenotypic value of the family". Individual phenotypic values have no significance using this method; their only purpose is in determining the family mean. Full or half sib families may be used. The effectiveness of between family selection is based on the fact that deviations between individuals, caused by the environment, cancel each other out in the mean value of the family. The result is that the phenotypic mean of the family becomes a close measure of its genotypic mean (Falconer & Mackay, 1996).

This method is most advantageous when environmental deviations are the main portion of the phenotypic variance, or simply, when the heritability is low (Falconer & Mackay, 1996). However, if environmental variation is common to members of a family, it can reduce the efficiency of between family selection. In other words, if some families are exposed to differing environmental conditions, they are going to respond differently and the phenotypic values measured may not be a true reflection of that family.

The family size, or number of individuals in the families, is important in influencing the effectiveness of between family selection (Falconer & Mackay, 1996). The mean phenotypic value represents the mean genotypic value more closely when large family sizes are used. Therefore, conditions favouring between family selection are low heritability, large families and minor variation due to a common environment. Problems do, however arise from between family selection; these are due to the vicious circle between the intensity of selection and inbreeding. The rate of inbreeding should be kept to a minimum, therefore, no less than the minimum number of parents, or families, can be selected for the next generation. Furthermore, if the intensity of selection is to be maintained at a high level, the number of families selected must be at least twice to four times the minimum number of parents, or families (Falconer & Mackay, 1996). Therefore the breeder must reach a compromise and select a certain number of families that will allow for an optimum response while keeping inbreeding to a minimum.

1.5.2.1.4 Within family Selection

Falconer & Mackay (1996) defined the criteria for selection of within family selection as "the deviation of each individual from the mean value of the family to which it belongs, those that exceed their family mean by the greatest amount being regarded as the most desirable" and are selected to be parents. The methodology of this selection technique opposes between family selection since the family means are given no weight, they are only used to calculate the deviation. The major advantage of within family selection is when a large component of environmental variance common to members of a family exists, as it eliminates this non-genetic component from the variation that is acted on by selection. Furthermore, this selection strategy can reduce the rate of inbreeding as it does not make use of family means which tend to increase the rate of inbreeding (Falconer & Mackay, 1996).

1.5.2.1.5 Family-index Selection

Family-index selection, or combined selection, is the single trait selection method that should yield the most progress, as it takes all available information about an individual into account (Falconer & Mackay, 1996). In family-index selection, individuals are chosen based on a weighted index of between and within family selection (Lynch & Walsh, 2000). Thus, each individual is assigned an index value that is a weighting of its family mean and its family deviation. Individuals with the highest index values are then selected as parents (Falconer & Mackay, 1996; Lynch & Walsh, 2000). Cost, however, poses a problem when employing family-index selection. Pedigree records, a requirement for family-index selection, may be costly to obtain, rendering this selection technique impractical even though it is, theoretically, the most efficient method (Falconer & Mackay, 1996). Family-index selection is not appropriate for more complex situations, where there are more than two sources of information; in this case index selection should be used.

1.5.2.2 Multiple Trait Selection

1.5.2.2.1 Index Selection

Although single trait selection has had its uses in the past, Hazel & Lush (1943) purport that selection for an index, giving suitable weight to each trait, is more effective than single trait

selection, or for multiple traits with an independent culling level for each trait. After all, an animal's practical value is influenced by multiple traits, each to a varying degree (Hazel, 1943). Hazel (1943) was the first to extend the selection index to the animal kingdom following Smith's (1936) development of the index for plant lines.

When multiple traits are used in the estimation of genetic merit, they may be combined into a single figure known as a selection index (Manson, 1972). The construction of an index to maximise genetic gain, and yield the most rapid possible improvement of EV, requires reliable information of the genetic parameters for each of the traits included in the index, as well as a relative economic weighting for each. To be specific, the phenotypic standard deviation, the heritability of the traits, the phenotypic and genetic correlations between the traits and the relative EV of the traits are needed to predict the genetic and financial worth of an animal (Dalton, 1981; Hazel, 1943). Logically, the gain made for each trait should be weighted by the relative EV of that trait (Hazel, 1943), ensuring that further progress can be achieved in the economically important traits.

The index is computed to derive an estimate in which the various traits are appropriately weighted to give the best prediction of the animal's breeding value (Dalton, 1981). It is important that several characters are simultaneously included in the breeding programme, as EV is dependent on more than one character (Falconer & Mackay, 1996). For example, the profit made from broiler breeders depends on their fertility, hatchability, growth rate, feed utilisation efficiency and carcass qualities. Therefore the advantage of using index selection is that no economically important traits will be ignored during selection. In certain cases, a restriction may need to be imposed preventing further change to a trait by manipulation of the economic weights (Hogsett & Nordskog, 1958). This may be necessary when genetic change occurs in an unfavourable direction and negatively affects traits correlated with it. It may also prove useful to fix traits if they are at a satisfactory level thereby placing more focus on those traits that need improving. Although restricting the selection index to suit the objectives of the breeder is attractive, it does negatively affect the efficiency of the index towards the traits of importance.

The difficulty of achieving significant responses when selecting for more than one trait arises from genetic antagonisms that may exist between traits, and a decreased selection intensity that will result when many characters are selected (Lerner, 1958). Due to the positive and

negative correlations that exist between the variety of traits that are important for the overall performance of a commercially successful strain, the selection that is directed towards all of these traits simultaneously may be worthless (Manson, 1972). This occurs when "the selection pressure applied towards trait A is counteracted by the movement of this very trait in the opposite direction as a result of a correlated response to a selection for trait B" (Lerner & Donald, 1966). Even though there is no solution to permanent genetic correlations, index selection can minimise the obstacles that they form in the breeder's path (Lerner, 1958). Hazel (1943) believed that the biggest challenge facing the success of the index is the unpredictable nature of the environment.

Selection indexes may not be widely applicable as they can be unique to the circumstances found in a group of animals at one locality (Hazel, 1943). There are various reasons for this; firstly the relative EV's of traits may vary due to locality, breed or a particular market. The genetic composition of animals may differ due to exposure to distinct breeding systems. Standard deviations for the traits may also vary due to different managerial practices. Lastly, sampling errors of the genetic constants are inevitable due to the general small size of groups that are available for data extraction. Furthermore, the selection index should be treated as a dynamic index, allowing frequent reconstruction of the index accounting for economic and performance modifications (Lin, 1978).

1.6 Consequences of Selection

The purpose of selection is to effect an improvement in a certain trait or a variety of traits. Thus, the advantages of selection procedures are vast, as the end product is shaped to deliver the requirements of a certain market. However, the good must come with the bad. There are various disadvantages associated with selecting organisms to satisfy the aim of man and these must be discussed following the testimony given regarding the success of genetic selection. These drawbacks are nature's way of preventing organisms from straying from what is normal and is required for the basic functioning of life. Some of these consequences of selection are discussed below.

1.6.1 Biological Limits of Selection

"Selection limits (or selection plateaus) are extreme levels of production which cannot be surpassed" (Fairfull & Gowe, 1990). A limit to the genetic improvement of animal productivity will always exist (Orozco, 1979). Orozco's (1979) examination of biological limits reveals that poultry researchers believed that limits had already been attained in 1979. Eleven years later Fairfull & Gowe (1990) stated that the experimental evidence of selection limits was not convincing. Subsequent studies, some of which have been discussed above, provide ample proof that selection limits had not been reached. Although a portion of this improvement is due to advances in nutrition and management, the greatest contributor remains the genetic selection applied to the birds.

This, however, does not mean that selection limits cannot be reached. Orozco (1979) states that there are many possible reasons to explain limits, however, there are two of particular importance. The first is the loss of genetic variability, as improvement of the selected population is prevented if no new genes are introduced. The second involves the biological limits of the animal, which once surpassed, the animal is no longer viable. This would be an example of natural selection confronting artificial selection. When natural selection acts against artificial selection, one of the most significant consequences is a deterioration in the fitness of the individual, loss of the ability to produce offspring. Natural selection is triggered when the value of a trait strays far from the starting point, thereby disturbing the equilibrium.

Another possibility for a levelling in performance in a population are negative correlations that exist between the economic characters influencing the performance of the bird, and hence the population (Yamada, 1958). Fairfull & Gowe (1990) believed that the most likely cause of a selection plateau is the attainment of a physiological or biological limit by the bird. The biological limit for broilers may exist at the point where their organs can no longer support the substantial increase in meat yield, and the increasing demands that would be placed on them. This biological limit may exist in the near future in some broiler strains.

1.6.2 Immune Response

Selection for high production potential does not come without negative consequences (Cheema *et al.*, 2003). Cheema *et al.* (2003) performed a study comparing the

immunocompetence of the 2001 Ross 308 strain and 1957 ACRBC strain when given diets representative of those being fed in 1957 and 2001. The data suggest that the relative growth of both primary and secondary lymphoid organs of the modern day broiler is reduced. Furthermore, the ACRBC strain displayed significantly higher total IgM and IgG responses than the Ross 308. Thus Cheema *et al.* (2003) concluded that fast growing strains of poultry have a relatively weaker antibody response, and disease resistance potential, than the slow growing types from which they were selected. These changes in antibody responsiveness may be a correlated response to selection for improved broiler production traits, including body weight. Further challenges facing breeders is that broilers are reaching target weights at younger ages, thus less time is available to implement an effective vaccination programme (Nicholson, 1998). *In ovo* vaccination would be a possible solution to this problem.

1.6.3 Skeletal Disorders

Skeletal disorders are predominant in rapidly growing broiler chickens (Julian, 1998) and are the cause of considerable economic loss to the industry due to condemnation, culling and death of the affected birds, since affected birds are, in most cases, immobile and cannot gain access to food and water (Bouzari *et al.*, 2005). It is in the interest of breeders to select for liveability traits in order to optimise the health of the birds. Bouzari *et al.* (2005) performed a study which showed that most of the clinical signs, gross pathological changes of muscles and skeletal disorders were significantly correlated to weight and age. Skeletal disorders, detected at slaughter time, were most common in the oldest and heaviest birds. A possible solution is a reduction in the length of the rearing period.

1.6.4 Fat Deposition

Lin (1981) concluded, from various studies, that a consequence of genetic improvement in body weight, growth rate or FCE is the deposition of excess carcass fat. Lin (1981) investigated possible reasons for increased fat deposition in broilers and found when selection is directed towards fast growth rate, increased feed intake has resulted. This increased feed intake may be used for fat deposition once muscle growth and maintenance requirements are satisfied. Several years later Gous *et al.* (1990) convincingly proved that the genotype is in fact not responsible for the high fat yields exhibited by broilers, but rather the way in which the birds are fed. As the growth potential of the broiler increases so the

level of protein required in the feed is increased. The main cause of excess fat deposition is therefore feeding a diet too low in protein.

Although the genotype of the bird is not directly responsible for increased fat deposition, selection for growth traits has increased the broilers appetite causing consumption of feed over and above their production requirements. This illustrates the importance of adjusting the diet according to the requirements of the modern broiler due to the increased possibility for excess fat deposition. This could be a serious disadvantage to the industry if the correct nutrient requirements of the broiler are not adhered to, since the consumer demands a healthy product to provide for their family.

1.6.5 Heart and Lung Capacity

A study involving the Ross 308 and ACRBC strain demonstrated that mortality of the Ross 308 was approximately twice as much when compared to the ACRBC, but was generally low at normal market ages (Havenstein *et al.*, 2003b). Late mortality that did occur in the trial was mostly due to leg–associated problems. Havenstein *et al.* (2003a) further investigated the possible reasons for an increased incidence of late mortality in the Ross 308 strain. They found that modern broiler strains had significantly lower heart and lung size as a percentage of live body weight than the ACRBC strain representative of 1957. Genetic selection for increased growth rate, and other growth related traits, would have caused this reduction. Modern broilers may be unable to service the respiratory demands of their bodies due to the relative size of their heart and lungs. Hence the problem of ascites that is experienced in contemporary broilers.

Havenstein *et al.* (1994) also suggested alternative contributory factors to the higher death rates of modern broilers. These included increased levels of total body fat and fat around the heart. Since liveability has a very low heritability (Kinney, 1969), it is imperative that management practices are suitable to allow the bird to reach it's full potential.

1.6.6 Reproductive Traits

Negative phenotypic and genetic correlations existing between growth-related traits and reproductive performance have resulted in increased fertility problems in male and female

lines from fast growing strains (Brillard, 2004). Selection for body weight in male lines has reduced the metabolic rate of spermatozoa and increased the percentage of dead and abnormal members, as well as negatively influencing the motility of spermatozoa (Chambers, 1990). Furthermore, males from high weight lines produce ejaculates of greater volume, but lower concentrations of spermatozoa, and tend to exhibit reduced libido and mating frequency. In the female line, percentage egg production, fertility and hatchability of fertile eggs, and sexual maturity are negatively related to high body weight (Maloney *et al.*, 1967). Furthermore, selection for body weight has lead to an increased incidence of abnormal eggs (double yolks, extra-calcified shells, compress-sided eggs generally named EODES or erratic oviposition and defective egg syndrome), internal laying, and progressive regression of developing follicles (Chambers, 1990).

Further consequences of long term selection for growth-related traits in male and female breeders is the natural tendency to reach sexual maturity at earlier ages if environmental conditions are not controlled (Brillard, 2004). Subsequent reproductive performance, such as limited testicular development, is severely affected if the situation is not avoided, resulting in limited sperm output in males, larger numbers of non incubatable eggs and a rapid decline in the reproductive performance of both sexes.

These reproductive problems are not as prominent in pullets that are restrict fed during rearing, and it is for this reason that commercial broiler parent flocks are restricted during rearing to enhance normal egg production (Chambers, 1990). In addition to controlling nutrition of the breeders, environmental control is also very important, particularly the photoperiod that the birds are exposed to.

1.7 Conclusion

It is overwhelming to consider the immensity of broiler research that has been performed since the onset of the industry. However, it is comforting to know that behind the objective of each paper lies the sole purpose for performing any research; to maximise the profit achieved or reduce the costs incurred by any broiler operation. This thesis fits comfortably in the mould and delves into the heart of the matter.

Following the thorough discussion of genetic selection and the role it has played in the broiler industry, the subsequent chapters will deal with practical selection procedures performed on a simulated population of breeder hens and cocks to assist in the comparison of the five selection procedures.

CHAPTER 2
SINGLE TRAIT SELECTION

More than 50 years ago Osborne (1957) examined the theoretical value of full-sib and complete sire family selection, index selection and individual selection. He found sire family selection to achieve greater gains, when a trait has a low heritability, than full-sib family or index selection. Furthermore, index, full-sib and sire family selection proved to be more efficient than individual selection when the heritability was low. It is worthwhile examining the results from studies that have been performed on broilers and laying hens, to determine the accuracy of the simulated models.

Kinney *et al.* (1970) performed an actual selection study, over nine years, determining the direct response to selection for short term rate of egg production in White Leghorns and the correlated response in sexual maturity, egg weight and body weight. The evaluated selection techniques included; individual, half-sib family, full-sib family and index selection. The average genetic gain in egg production, for eight generations of selection, was largest for sire family selection, followed by index, individual and finally dam family selection. Upon standardisation of the response for the phenotypic variance of individual rate of production, and the amount of selection, the greatest average response was in fact from individual selection. The sire family, index and dam family selection followed.

Garwood & Lowe (1979) extended the study performed by Kinney *et al.* (1970) by three generations to determine whether the relative efficiencies of the selection strategies remained unchanged. Yet again index and sire family selection proved superior to individual selection for average genetic gain in short term rate of egg production. In further agreement, individual selection surpassed the remaining selection techniques when gain was standardised.

De Guisti (2003) developed computer models using Microsoft Excel 2000 to compare the efficiency of individual, between family, within family and family-index selection when applied to four traits. The selection techniques were applied to an artificially, randomly generated population of laying hens. The direct response to selection for egg weight, egg production, age at first egg (AFE) and body weight was determined. Between family selection proved

superior when applied to egg production, family-index selection superior when applied to egg weight and AFE, and individual selection was superior when applied to body weight. All comparisons were made up to 10 generations.

There are various rules of thumb stating under which circumstances certain selection techniques will outperform others. Falconer & Mackay (1996) state categorically that family index selection is superior to the three simpler methods, individual, between family and within family selection. It is therefore under varying conditions that the three simpler methods compete for superiority. The first basic rule is that family selection techniques are more efficient than individual selection if the trait under selection possesses a low heritability (Kinney *et al.*, 1970; Lynch & Walsh, 2000; Osborne, 1957). When comparing individual, between family and within family selection over a range of phenotypic correlations of members of a family, individual selection is the victor over most of the range (Falconer & Mackay, 1996). The reason being that between family selection acts only on the variance between family means, and within family selection only on the variance within families, whereas individual selection acts on the whole of the additive genetic variance. When the phenotypic intraclass correlation is low, representing low sib-correlations, thus a low heritability, and barely any resemblance from a common environment, between family selection is superior to individual selection. Upon the rare occurrence of large sib-correlations, due to a substantially large common environment, within family selection will perform better than individual selection.

A point that deserves mentioning and must be cautioned when using artificial selection, is that of inbreeding. When using between family selection, entire families are selected as parents for the following generation (Falconer & Mackay, 1996), thus resulting in a large reduction in genetic variance. The rate of inbreeding is consequently greatly increased when compared to individual selection where individuals are chosen as parents (Falconer & Mackay, 1996). Family index selection, also utilising family means, will increase the rate of inbreeding. In contrast, within family selection, using similar principles to individual selection, tends to decrease the rate of inbreeding since parent selection is based on the best individuals from a family.

A further disadvantage of between family selection over within family selection, is the reduction in the between family variance caused by the disequilibrium generated by selection

(Falconer & Mackay, 1996). Therefore within family selection has the advantage of acting on a larger amount of additive variance. A final and essential consideration is that of economics. Although family index selection is known to be superior, obtaining both individual and family records may prove to be economically impractical.

Having discussed the above points focussing on the advantages of a certain selection strategy over another due to more favourable conditions, it must be considered that the simulated selection techniques have the drawback that they are not able to take into account the effect of the environment (apart from the heritability measure of each trait), nor the negative effects associated with inbreeding. However, they are a very useful and convenient tool to demonstrate the principles of each technique and compare the different selection techniques given their limitations.

Further to the importance of the relative merits of the selection procedures is the response of the traits to the single trait selection procedures. The following authors have selected a primary trait of interest in a population of birds over a number of generations focussing on the response of the primary and correlated traits to selection.

Poggenpoel *et al.* (1996) performed a selection experiment focussing on hen-housed egg production from the period 1962 to 1990 on a population of White Leghorns. Emphasis was placed on egg production for the first 10 years of the experiment resulting in a large gain of 44%. There was, however, a decline in AFE and body weight, particularly in egg weight, due to the correlated response to selection. Following this, selection pressure was applied to egg weight, resulting in a significant decline in total egg production, and a surprising decline in body weight, although not as marked as when selection was applied to egg production. The authors found the genetic correlation between egg production and egg weight to remain constant throughout their study.

Sharma *et al.* (1998) performed a selection experiment over 16 generations based on hen housed egg production to 40 weeks on a White Leghorn population. The correlated response was determined in body weight at 20 and 40 weeks of age, AFE and the average weight of the eggs at 40 weeks of age. A significant improvement resulted in hen housed egg production, a sharp decline in egg weight, which was later controlled by a culling programme, a sharp decline in AFE, a non-significant change in 20 week body weight and a significant

decline in 40 week body weight. Hen housed egg production experienced a reduced genetic gain in the latter generations, possibly due to the shift towards egg weight, which also positively affected body weight, at both ages, in the later generations. The authors also noted the weakened response to selection in the last two periods of selection, in contrast to a positive response in the first two periods.

Liu *et al.* (1994) presented results on a selection experiment based on divergent selection for body weight at eight weeks of age, performed for 36 generations on White Plymouth Rock lines. Rather remarkably, and proving the power of genetic selection, an eight-fold difference resulted between the high and low weight line. The authors also noted the declining response to selection that was exhibited in the later generations compared to the earlier generations.

The objective of this portion of the study, focussing on single trait selection, was to compare the theoretical and simulated response in genetic gain to four single trait selection methods in a simulated population of broilers; this being a more rapid means of comparing these methods than conducting selection experiments with broilers.

Not all traits considered for the economic model were used for the selection strategies in this study. Hatchability and fertility were not included since they possess a poor heritability, making it inherently difficult to achieve significant progress with either trait. Mortality also exhibits a low heritability since it is largely influenced by the environment, furthermore, identification of the reason for mortality is particularly challenging. Body weight and feed conversion ratio (FCR) are directly related thus it is unnecessary to include both traits in a single selection procedure. Contrary to previous beliefs, FCR can be directly selected for, as proved by Pym (1985), however body weight was chosen for the present exercise. Furthermore, Hogsett & Nordskog (1958) identified egg production, egg weight and body weight as the main contributors to the genetic economic value (GEV) of a breeding flock, while Kinney & Shoffner (1965) focused on body weight, sexual maturity and egg production in their study. The most relevant traits have become obvious due to their recurring occurrence in the studies quoted above. Although only four traits were selected for this exercise, it is possible to include any trait in which the heritability and genetic and phenotypic correlations are known using the same principles.

2.1 Materials and Methods

Five selection techniques were applied to a simulated population of broilers in order to determine the rate of genetic progress achieved. These were individual selection (IS), between family selection (BFS), within family selection (WFS), family-index selection (FIS) and index selection. These selection strategies were applied to mature egg weight, egg production to 60 weeks, age at first egg (AFE) and body weight at 35 days. The simulated population of broilers was generated in Microsoft Office Excel 2007 using normally distributed random numbers to describe the traits of interest in the individuals making up the population. The following are the means of the traits in the base population, which were obtained from industry: 67 g, 180 eggs, 175 days and 1800 g respectively. The coefficients of variation (CV) used to generate the population were 6% for mature egg weight, 14% for egg production to 60 weeks, 7% for AFE and 6% for body weight at 35 days. Traits that are largely influenced by the environment would have a higher CV since they would naturally exhibit a higher variation. Egg production, having the lowest heritability, had the highest CV in this study, while egg weight, AFE and body weight exhibited low CV's since they possess high heritabilities.

Progress achieved for each of the selection strategies over 10 generations was predicted using two techniques, the first being the more common theoretical technique whilst the second involved direct selection from the simulated population. The theoretical method involved calculation of the response using the equations of Falconer (1981). The intensity of selection, heritability of the selected traits and phenotypic standard deviation (SD) of the previous generation was multiplied to calculate the response to selection, or superiority of the parents over the population from which they were selected. These factors were not naturally introduced into the population, but rather imposed in the form of the response equation. Consequently, this method did not make use of the randomly generated population of birds other than to provide a value for the SD of the parents for each trait, which was calculated after each generation of selection. These average values were used as a means of preventing the population from making unrealistic progress each generation. The simulation method was assumed to be a more realistic representation of reality.

The effectiveness of the four selection techniques regarding the progress that was made for each trait was investigated and compared using tables and graphs. The relative effect of

selection for egg production on body weight, and *vice versa*, was also investigated. Graphs illustrating the relationship between the results obtained from the theoretical simulations and those obtained with the use of a correction factor are also presented.

2.1.1 Assumptions made in generating the models

Because the SD of each trait is used in the equation to calculate the response to selection a realistic estimate is required in order to give an accurate response. If the SD of the selected parents were used, this would cause the value to be too low. Additionally, if the SD of the entire population was used, this value would be too high. Therefore, an average of the SD of the selected parents and the entire population was used as a realistic estimate of the SD. This value was used to generate the individuals in each generation, except for the first.

Other assumptions include:
- Selected parents were randomly mated against each other each generation.
- For BFS, WFS and FIS, the family size was five (n = 5) and the families were full sib families (r = 0.5). It was assumed that the first five values of each trait would represent one family and the next five values would represent the second family, thereby making up 100 families consisting of five individuals in each family.
- No inbreeding was present for any of the selection strategies, regardless of the constant selection intensity and population size.
- Equal numbers of male and female birds were present in each generation. The values for egg production, egg weight and AFE for the breeder males would have been representative values taken from their female progeny, illustrating their ability to positively contribute to these reproductive traits.
- The environment did not have an effect on any of the traits; the natural influence of the environment on each trait is reflected in the value of the heritability.

The above assumptions are based on those from De Guisti (2003).

2.1.2 Starting Population

A table was constructed in Excel to describe the parameters of the four traits that were used in the study. The parameters included the heritability, the mean and the SD. The heritability estimate for each of the traits was taken as an average value from the literature (Table 1.3).

The SD's were calculated by multiplying the CV for each trait by the mean value. A correlation matrix (Table 2.1) was constructed in which the genetic correlation between each pair of traits obtained from the literature was entered.

Table 2.1 Heritability, genetic (above) and phenotypic (below) correlations between mature egg weight, egg production to 60 weeks, AFE and body weight at 35 days

Genetic (above) and phenotypic (below) correlations	h²	Egg weight	Egg prodn to 60 wks	AFE	Body weight @ 35d
Egg weight	0.51	■	-0.5	0.4	0.25
Egg prodn to 60 wks	0.1	0.02	■	-0.4	-0.55
AFE	0.4	0.2	0.01	■	0.4
Body weight @ 35d	0.52	0.3	-0.04	-0.2	■

The starting population was generated using the Cholesky Decomposition (Weisstein, 2006) to correlate the traits according to their genetic correlation coefficients. The mean, CV and SD for each of the four traits was entered into the cells above where the population was due to be displayed. A second row of SD's was entered to calculate the average SD of the selected parents and the entire population as explained previously (Cell Q10, R10, S10 and T10). This is illustrated in Figure 2.1.
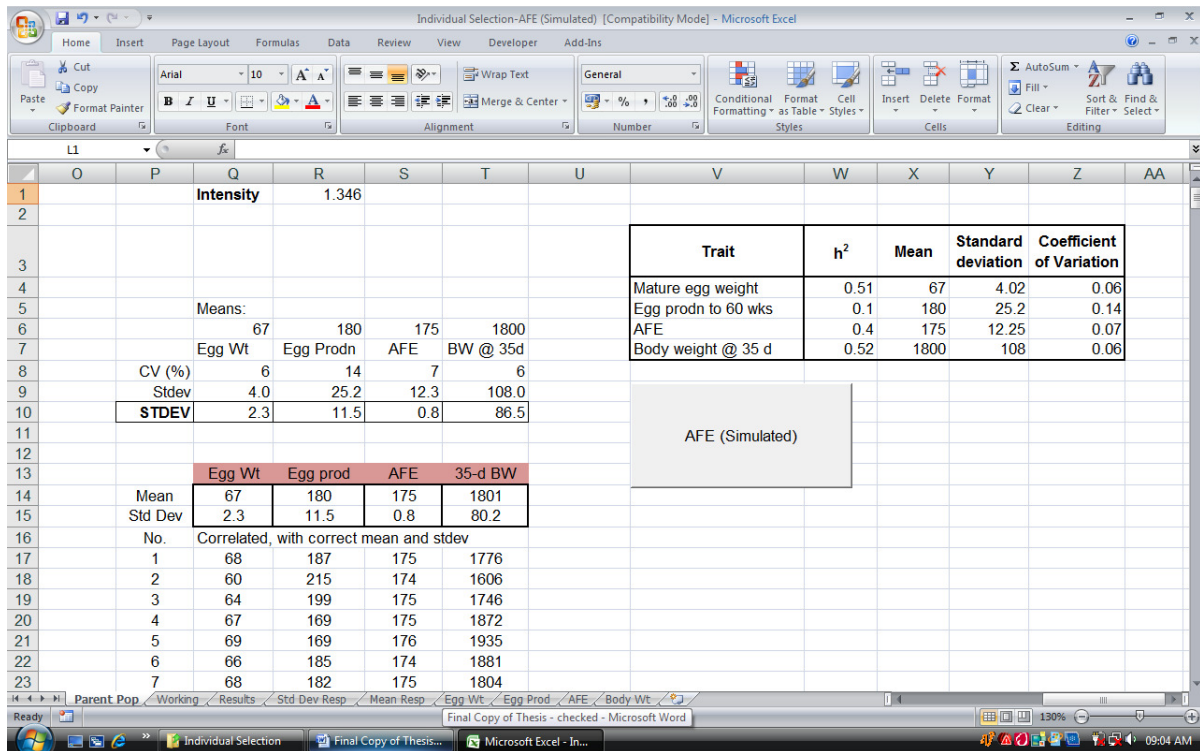
Figure 2.1 The Microsoft Excel worksheet of the Starting Population illustrating the first few values of the randomly generated population, the mean, SD and coefficient of variation

The starting population consisted of 500 randomly generated individuals displaying the values of four traits. The values for each trait describing each individual were generated by multiplying the correlated random number with the corresponding initial SD and then adding the mean value of the trait. An example of this formula for egg weight:

$$Egg\ weight\ (g) = Correlated\ random\ no. \times SD\ (4.0) + egg\ weight\ starting\ value\ (67g)$$

The formula was further modified using the IF function which returns a value based on a condition specified to it. It was used to set a limit to the progress that could be achieved in each trait, based on the capacity of the bird. The limits set were 80 g for egg weight, 215 eggs for egg production, 140 days for AFE and 2500 g for body weight. If the selection procedure returned a value in excess of these limits, the above limit was displayed; alternatively, the calculated value was displayed. The overall means and SD's of the traits in

the simulated population were calculated and displayed in cells Q14 & 15, R14 & 15, S 14 & 15 and T14 & 15.

2.1.3 Individual Selection (IS)

Improvements in the population mean of each of four important traits in broiler production, brought about by selection for each trait individually, were compared using two methods of evaluating such progress, namely a theoretical and a simulated approach. The theoretical method will be described first, using egg weight as an example.

The starting mean of each of the traits (in the base population) was entered in the cell above the table in which the population values were to be calculated and displayed; the population values would be based on these starting means. Random numbers were generated, by pressing F9, until the mean and SD of the population loosely corresponded with the mean and initial SD that was entered. The population mean and SD were then copied and the values were pasted into two new worksheets named "Macro" and "Results". These values were entered into two worksheets as a macro was to be run using these values. The macro recorded each calculation that was made in the present generation, so that the calculations did not have to be repeated in generations to follow. When recording a macro, Excel will store the information that the user has performed as a series of commands.

The data were sorted in ascending or descending order, depending on the trait under consideration. When selection was applied to egg weight, all egg weight values would be sorted with the highest values at the top. It is imperative that all traits are highlighted, so that the values that correspond to egg weight are moved to the appropriate position along with the egg weight values.

The proportion of individuals that were selected in this study was 22%. This corresponded to 110 individuals, and an intensity of selection of 1.346 (Falconer, 1981). The top 110 individuals with the highest egg weights (having been determined by sorting) were highlighted (again every trait had to be highlighted) and copied into a new "Working" worksheet. Two rows were inserted above the 110 selected parents, and the mean and SD of each trait was calculated. The mean egg weight of the offspring of the following generation was calculated

in the same worksheet by adding the response to selection for generation one to the mean value of generation one before selection, using the following formula (Falconer, 1981):

$$R = i \times h^2 \times \sigma_p + trait\ mean\ for\ the\ previous\ generation$$

Where i = 1.346

h^2 = 0.51

σ_p = 4.0

and the mean = 67 (for egg weight)

Direct selection was applied to egg weight, therefore a different formula was required to calculate the response in the correlated characters. The correlated characters in this case included egg production, AFE and body weight. The correlated response to selection was calculated using the following formula (the example shows direct selection for egg weight with the correlated character egg production) (Falconer, 1981):

$$CR_y = i \times h_x \times h_y \times r_A \times \sigma_{py} + trait\ mean\ for\ the\ previous\ generation$$

Where i = 1.346

h_x = 0.714 (egg weight)

h_y = 0.316 (egg production)

r_A = -0.5

σ_{py} = 25.2

and the mean = 180 (for egg production)

In the above formula, h_x and h_y are the square root of the heritability for egg weight and egg production, respectively, r_A is the genetic correlation between egg weight and egg production, and σ_{py} is the SD of egg production from the previous generation. This formula was also used to calculate the correlated response to selection for AFE and body weight using the corresponding parameters for each. Once these values were determined, they were pasted where the starting means were located from which the population was generated. The macro was then stopped and a button was inserted that would be pressed each time the macro was required to operate. The population would now be generated from the new means that were inserted. It was stated earlier that it was necessary to generate the population with a SD that

was halfway between that of the selected parents and the entire population. Therefore, the formula that was used to generate the population using the initial SD was now changed to incorporate the average SD. This change was made for every individual and every trait.

Random numbers were then generated until the mean values for all the traits of the population loosely corresponded with those that were pasted from the worksheet calculating the response to selection. Additionally, the SD of the population had to correspond with the new SD that was being used. These means and SD's were copied, and the values were pasted into the worksheets "Macro" and "Results" as explained above. The macro was then run and the process repeated until 10 generations of mean values were produced.

This process was repeated for selection of egg production, AFE and body weight. Differences arise when selection is applied to AFE, as this trait must be sorted in ascending order (as the aim is to reduce the number of days to sexual maturity) and the direct and correlated responses to selection formulae were applied to different traits as selection goals were changed. Therefore a new macro was run when selecting for each trait. The formula for calculating the mean value of the offspring was also changed when selecting for AFE. The only modification was that the response equation (for both direct and correlated response to selection) was subtracted from the mean of the previous generation. The reason for this adjustment is that selection was made for a decreased AFE. The above changes apply to all selection techniques.

In the simulated approach to evaluating the progress made by IS a similar method to that described above was used, but in this case the response equation was not needed and was thus excluded. The assumption in using this method was that realistic values for each of the traits, based on current levels of production and reliable estimates of heritability and genetic correlations obtained from the literature, could be generated and which could, in turn, be used to simulate an actual selection experiment.

As with the theoretical method the starting values were inserted above the population and random numbers were generated until the population mean and SD loosely corresponded with the starting values and initial SD. These values for the population were then copied and pasted into the "Results" worksheet. A macro was then run given the following instructions. The population was highlighted and sorted according to the desired trait. The top 22% of the

population was then copied and the values pasted into the "Working" worksheet. The mean and SD for each of the parental traits was calculated and used to determine the response to selection for the following generation. The resulting means of the parents were not simply passed onto the next generation, as a limitation is imposed by the heritability of the trait. Therefore the heritability was used to determine the response. The mean value of the trait for the population, before selection, was subtracted from the mean value of the trait for the selected parents, and multiplied by the heritability. This response to selection was added to the mean of the previous generation to determine the mean value of the offspring for the following generation.

The mean value of the offspring for the following generation was then copied and pasted into the "Parent Pop" worksheet where the starting means were located. The macro was stopped and the SD used to generate the population was changed to the average value. This process was repeated for 10 generations and all four traits.

2.1.4 Between Family Selection (BFS)

The BFS model was built up from the IS model. The process used for the theoretical method will be described first. The first changes that were made included calculating the family means of each trait for each family of five in the original worksheet illustrated in Figure 2.2. Four columns adjacent to the population values represented the family means for each trait. The mean value for each family was displayed adjacent to the first member of the family, followed by four blank spaces. The reason for this will be explained later. In the same worksheet, the value for r (0.5) and n (5) was entered.

A second worksheet named "Ranked Means" was set up in which the entire population was copied, and the values pasted in the new sheet. The adjacent cells were also used to calculate the family means. This time the family means were displayed in every cell; there were no blank spaces between each mean. The means cannot be ranked or sorted if blank spaces are left between them as the individuals from each family would get mixed up in the process and it is important that the family values are kept together, since the whole family is selected as a unit.

The family means from the first worksheet were copied and the values were pasted into the cells adjacent to the newly calculated family means in the "Ranked Means" worksheet. The family means with the blank spaces were now used to calculate the variance of the family means. If these were calculated from the family means that were replicated five times for each family, inaccurate estimates would have resulted. The variance of the entire population for each trait was then calculated from the population values in the "Ranked Means" worksheet. The value of t was calculated by dividing the variance of the family means by the variance of the population. The resultant worksheet is illustrated in Figure 2.2.
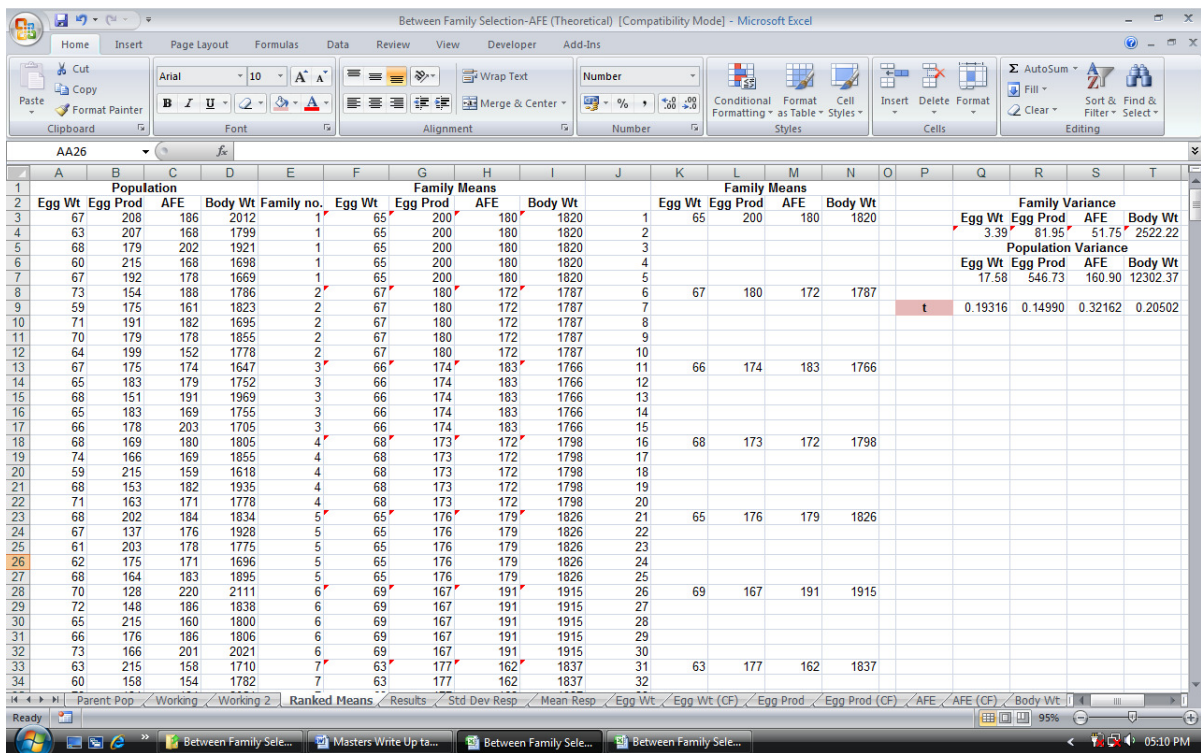
Figure 2.2   The Microsoft Excel file ("Ranked Means" worksheet) for Between Family Selection showing the first six families from the population, the family means, the standard deviation and mean of the family means, the family and population variance and t

The heritability of the family means for BFS was determined for use in the response equation. These were calculated in the same worksheet as the parent population using the following formula (Falconer, 1981):

$$h_f^2 = h^2 \times \frac{1 + (n-1)r}{\sqrt{n\{1 + (n-1)t\}}}$$

h^2_f for egg weight:

Where $h^2 = 0.51$

$n = 5$

$r = 0.5$

$t \rightarrow$ would be for egg weight

The starting means of each of the traits (in the base population) was entered, and random numbers were generated until the population mean and SD loosely matched the starting mean and initial SD. The mean and SD of the population were copied and the values were pasted into the "Results" worksheet and the "Working 2" worksheet for reference in the response equation. The SD was pasted a second time in the "Results" worksheet, as the new SD would be calculated from these values that would be replaced each generation. The macro was then run given the following instructions.

The entire population for each trait was copied, and the values were pasted into the "Ranked Means" worksheet. The family means that would have been automatically generated with the individual values were also copied, and the values were also pasted into the "Ranked Means" worksheet in the allocated space. As all formulae were already in place to calculate the mean, SD and variance of the family means as well as the population variance and the heritability of the family means, pressing F9 would recalculate these values according to the new values of each trait in the population. The section representing the replicated family means would also re-calculate the new family means according to the population values that were entered.

The entire population for each trait and the replicated family means in the "Ranked Means" worksheet were highlighted together, copied and the values were pasted into another worksheet. Still highlighted in the new worksheet, the values were sorted so that the family means, of egg weight in this case, were arranged in descending order. It was important that the population values were also highlighted, so the individuals from each family that corresponded to the highest family means would be moved to the top of the worksheet as well.

When using BFS, the individuals are selected based on their family means. For example, if a certain family has the highest mean for egg weight, all the individuals from that family will be selected as parents for the next generation, meaning some above and below average individuals will become parents. One hundred and ten individuals were selected to be parents for the next generation, corresponding to 22 families. The top 110 individuals according to their family means were then copied and the values were pasted into the "Working" worksheet. F9 was pressed to calculate the mean and SD of the selected parents. The mean value of the offspring was calculated in the same manner as for IS, with the following modifications made to the response equations (Falconer, 1981):

Direct Response to Selection:

$$R_f = i \times \sigma_p \times h_f^2 + trait\ mean\ for\ the\ previous\ generation$$

Where i = intensity (1.346)

σ_p = phenotypic standard deviation

h^2_f = between family heritability

Correlated Response to Selection:

$$R_f = i \times h_x \times h_y \times r \times \sigma_p + trait\ mean\ for\ the\ previous\ generation$$

The resulting values were pasted in the original location of the starting means. The macro was stopped and the SD used to generate the population was changed to the average value.

The process above was repeated using the macro where necessary to shorten the procedure. Ten generations of values were generated for egg weight, egg production, AFE and body weight.

In the simulated approach to evaluating the progress made by BFS a similar, although much simpler method to that described above was used. There was no need for calculation of the population or family variance which was used to calculate t for use in the response equation. Once the population values for generation one were generated, the macro was given the following instructions. The entire population was copied and the values pasted into the

"Ranked Means" spreadsheet. Here the family means were determined adjacent to the population values. It was important that the mean of the family was displayed adjacent to each individual of the family. The newly calculated family means as well as the population values were copied and the values pasted into the "Working 2" worksheet. All values still highlighted, the data was sorted according to the family mean under selection. The family means having served their purpose, the top 110 individuals were then copied and their values pasted into the "Working" worksheet. Upon pressing F9, the mean and SD of the selected parents was displayed adjacent to the response equation that was also used for the IS simulation method. These values of the offspring for the following generation were pasted into the location of the starting values and the macro was stopped. This process was repeated for 10 generations and all four traits.

2.1.5 Within Family Selection (WFS)

The BFS Excel file was modified for use in WFS, since WFS is based on the deviation of each individual from the mean value of the family to which it belongs, rather than selecting the family as a unit. Four columns representing the deviation of each individual's traits from its family mean were inserted between the sections that calculated the family means in the "Ranked Means" worksheet.

The heritability of within family deviations was then calculated using the following formula (Falconer, 1981):

$$h_w^2 = h^2 \times (1-r) \sqrt{\frac{(n-1)}{n(1-t)}}$$

h^2_w for egg weight:
Where $h^2 = 0.51$

      $n = 5$

      $r = 0.5$

      $t \rightarrow$ would be for egg weight

The procedure explained in BFS was followed for the theoretical method. However, the entire population and the deviations (instead of the family means) that were calculated in the

"Ranked Means" worksheet were copied, and their values were pasted into a new worksheet. In the new worksheet the population values and the deviations were highlighted; the deviations were sorted in descending order (or ascending order if selection was for AFE) according to the trait that was selected for. The largest positive deviations of the selected trait were then displayed at the top of the worksheet. The top 110 individuals, from random families, with the greatest deviations with respect to the trait selected, were then copied and the values were pasted into the "Working" worksheet. F9 was pressed to calculate the mean and SD of the selected parents. The mean value of the offspring was calculated in the same manner as for IS, with the following modification made to the response equations (Falconer, 1981):

Direct Response to Selection:

$$R_w = i \times \sigma_p \times h_w^2 + trait \ mean \ for \ the \ previous \ generation$$

Where i = intensity (1.346)

σ_p = phenotypic standard deviation

h_w^2 = within family heritability

Correlated Response to Selection:

$$R_w = i \times h_x \times h_y \times r \times \sigma_p + trait \ mean \ for \ the \ previous \ generation$$

The results for egg weight, egg production, AFE and body weight were obtained by following the same procedure as BFS. This was performed for 10 generations each.

The procedure for the simulated method was much simpler than the theoretical method and very similar to the procedure used in the simulated BFS method. The only difference was the calculation of the deviation of each individual from its family mean. The top 22% of the population for the trait of importance was determined by sorting the deviations of each individual from the mean value of the family to which it belongs.

2.1.6 Family-Index Selection (FIS)

FIS is a strategy whereby individuals are chosen based on a weighted index of BFS and WFS. The BFS Excel file was modified for use in FIS. The theoretical method will be explained first. In the previous "Ranked Means" worksheet a row was inserted above the population values to calculate the mean of the population for each trait. Four columns adjacent to the family means were used to calculate P_f for each trait. P_f was determined by calculating the difference between the family mean and population mean for each individual. Four columns adjacent to the P_f calculations were used to calculate the index values using the following formula (Falconer, 1981):

$$I = P + \left\{ \frac{r-t}{1-r} \times \frac{n}{1+(n-1)t} \right\} \times P_f$$

Index value for egg weight:

Where P = individual's phenotypic value for egg weight

r = 0.5

n = 5

t → would be for egg weight

P_f → value for that particular individual

The family-index heritability was calculated using the following formula (Falconer, 1981):

$$h_c^2 = h^2 \times \sqrt{1 + \frac{(r-t)^2}{(1-t)} \times \frac{(n-1)}{1+(n-1)t}}$$

h^2_c for egg weight:

Where h^2 = 0.51

n = 5

r = 0.5

t → would be for egg weight

The same procedure that was followed for the above selection techniques was applied here. However, the individuals were now ranked according to their index values. Therefore,

individuals with the highest index values for the selected trait were considered as parents for the following generation. The mean value of the offspring was calculated in the same manner as for IS, with the following modifications made to the response equations (Falconer, 1981):

Direct Response to Selection:

$$R_c = i \times \sigma_p \times h_c^2 + trait\ mean\ for\ the\ previous\ generation$$

Where i = intensity (1.346)

σ_p = phenotypic standard deviation

h_c^2 = family-index heritability

Correlated Response to Selection:

$$R_c = i \times h_x \times h_y \times r \times \sigma_p + trait\ mean\ for\ the\ previous\ generation$$

FIS was performed on egg weight, egg production, AFE and body weight for 10 generations each.

The procedure for the simulated method was very similar to the theoretical method, the only difference being the calculation of response to selection.

2.1.7 Correction Factor

A correction factor, which takes account of the altered heritability value for each family selection technique, was determined for all selection techniques based on family means. Prediction of the progress achieved in each of the family selection techniques is achieved by multiplying this factor with the basal equation used in the individual selection response equation. Its purpose is to predict the response that should have been achieved with BFS, WFS and FIS. The resulting values were compared to those achieved by the selection methods applied. The correction factor formulae for the family selection models are below (Falconer, 1981):

Between Family Selection:

$$CF = \frac{1 + (n-1)r}{\sqrt{n\{1 + (n-1)t\}}}$$

Within Family Selection:

$$CF = (1-r) \times \sqrt{\frac{(n-1)}{n(1-t)}}$$

Family-Index Selection:

$$CF = \sqrt{1 + \frac{(r-t)^2}{(1-t)} \times \frac{(n-1)}{1 + (n-1)t}}$$

2.2 Results

The results are presented as tables and graphs to illustrate the direct response to selection resulting from both the theoretical and simulated methods of selection for each of the four single trait selection strategies. Additionally, graphs are used to illustrate the effect of each selection procedure on egg production when selection is directed towards body weight and *vice versa*. Finally, a comparison is made of the response predicted following application of the correction factor with that obtained using the family selection techniques, and this is illustrated with the use of graphs.

2.2.1 Mature Egg Weight

Figure 2.3 illustrates that the theoretical response in egg weight to FIS and BFS is superior (produces the best response) to that made with IS and WFS, over all generations. Both FIS and BFS reach their limit in generation nine. The rate of increase resulting from IS is rapid up to generation two, but begins to level off thereafter. The rate of response appears to decline from about generation six. The response made with WFS is far below that of the other strategies. In generation 10, IS, BFS, WFS and FIS achieved proportional increases of 1.15, 1.19, 1.09 and 1.20, respectively, with SD's of 0.2, 0.1, 0.5 and 0.1, respectively.

The simulated response in egg weight to IS is highest, followed by WFS, FIS and finally BFS. Again, the rate of increase resulting from IS is greatest, but begins to level off at about generation six. WFS and FIS result in increases at the same rate, however WFS overtakes in generation seven and equals that using IS in generation 10. BFS results in slower increases but with no sign of levelling off and would most likely draw level to the other selection strategies soon after generation 10. This is an indication that BFS has maintained a satisfactory SD throughout the selection period. When the SD is reduced, it limits the improvement that can be made in the trait as the range of values in the population is reduced. In generation 10, IS, BFS, WFS and FIS achieved a proportional increase of 1.16, 1.13, 1.16 and 1.15, respectively, with SD's of 0.3, 2.3, 0.6 and 0.5, respectively.

The simulated methods of WFS and IS resulted in greater progress than the theoretical method, whereas the theoretical methods of BFS and FIS were superior to the simulated

methods. The highest response was achieved with the theoretical FIS and BFS, and the simulated IS methods, whereas the theoretical method of WFS, and the simulated method of BFS, produced the lowest responses.
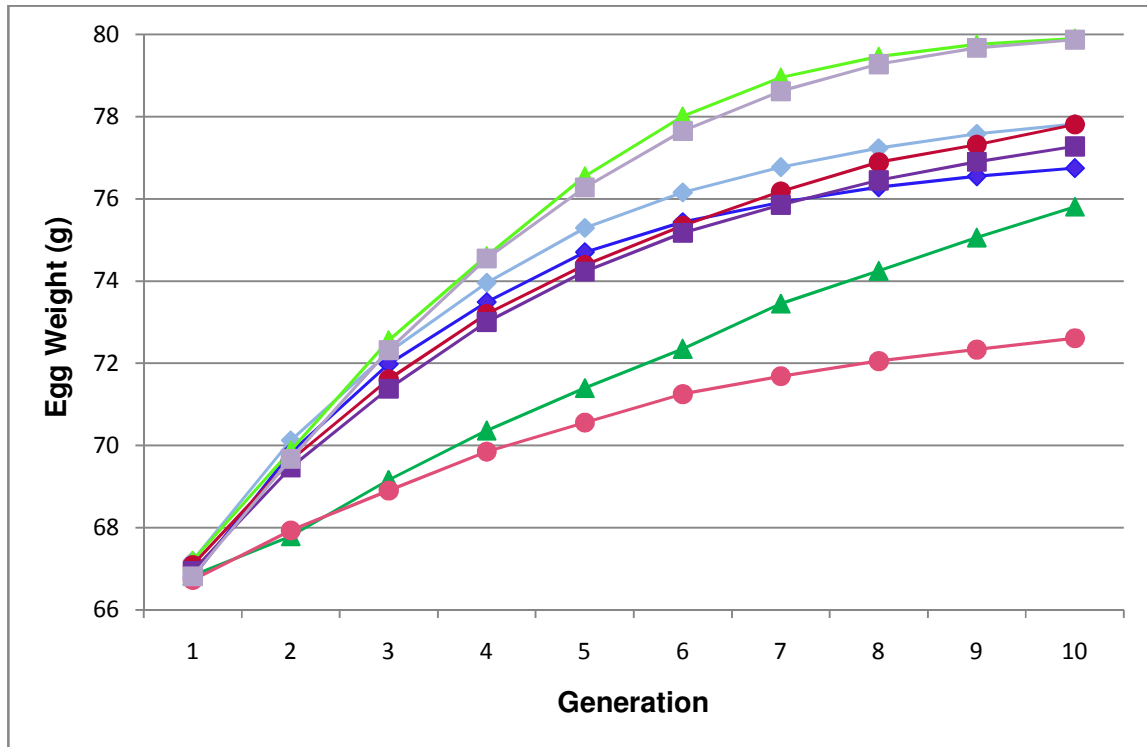
Figure 2.3 Comparison of simulated and theoretical selection techniques applied to the improvement of egg weight (Individual Selection ⇨ ◆ Simulated ◆ Theoretical, Between Family Selection ⇨ ▲ Simulated ▲ Theoretical, Within Family Selection ⇨ ● Simulated ● Theoretical and Family-Index Selection ⇨ ■ Simulated ■ Theoretical)

Table 2.2 The proportional increase in egg weight over ten generations of selection using both simulated and theoretical methods of individual, between family, within family and family-index selection

Generation	Individual		Between Family		Within Family		Family-Index	
	Sim.	*Theor.*	*Sim.*	*Theor.*	*Sim.*	*Theor.*	*Sim.*	*Theor.*
2	1.04	1.05	1.01	1.04	1.04	1.02	1.04	1.04
4	1.10	1.10	1.05	1.11	1.09	1.05	1.09	1.12
6	1.13	1.13	1.08	1.16	1.12	1.07	1.12	1.16
8	1.15	1.14	1.11	1.18	1.15	1.08	1.14	1.19
10	1.16	1.15	1.13	1.19	1.16	1.09	1.15	1.20

2.2.2 Egg Production to 60 weeks

The highest theoretical response in egg production was obtained using BFS followed by FIS, IS and WFS, as illustrated in Figure 2.4. The response using BFS increased at the same rate with FIS and IS, however, in generation four the rate of increase escalated and showed no indication of slowing. This illustrates that only BFS is able to maintain a reasonable SD throughout the selection period. The progress with IS and FIS is equivalent up to generation five, thereafter FIS surpasses IS, mainly due to FIS retaining a greater SD. The response using WFS begins to level off in generation three, never reaching the heights of the other selection strategies. By generation 10, IS, BFS, WFS and FIS achieved proportional increases of 1.05, 1.10, 1.03 and 1.07, respectively, with SD's of 1.0, 8.8, 2.9 and 3.0, respectively.

WFS and FIS competed for superiority in the response to selection using simulation. WFS resulted in a greater rate than any other selection strategy up to generation six, then drew level with FIS. The progress achieved with IS increased rapidly initially then levelled off at generation six. BFS never resulted in the same response as the other strategies resulting in increases in an irregular fashion. The increase did, however, show no sign of slowing and could possibly have overtaken the progress made with the remaining strategies past generation 10. By generation 10, IS, BFS, WFS and FIS resulted in a proportional increase of 1.05, 1.05, 1.06 and 1.06, respectively, with SD's of 1.3, 10.7, 3.2 and 2.5, respectively.

The theoretical and simulation methods of IS for egg production produced similar results, but the theoretical method was more efficient when using BFS and FIS. Conversely, the response to the simulated method was greater for WFS. BFS, for the theoretical method, and WFS, for the simulation method, produced the highest response and therefore successfully selected birds producing the maximum number of eggs to 60 weeks, whereas WFS, for the theoretical method, and BFS, for the simulation method, produced the lowest response.

Figure 2.4 Comparison of simulated and theoretical selection techniques applied to the improvement of egg production to 60 weeks (Individual Selection ⇨ ◆ Simulated ◆ Theoretical, Between Family Selection ⇨ ▲ Simulated ▲ Theoretical, Within Family Selection ⇨ ● Simulated ● Theoretical and Family-Index Selection ⇨ ■ Simulated ■ Theoretical)

Table 2.3   The proportional increase in egg production to 60 weeks over ten generations of selection using both simulated and theoretical methods of individual, between family, within family and family-index selection

Generation	Individual		Between Family		Within Family		Family-Index	
	Sim.	*Theor.*	*Sim.*	*Theor.*	*Sim.*	*Theor.*	*Sim.*	*Theor.*
2	1.02	1.01	1.01	1.02	1.01	1.01	1.01	1.02
4	1.03	1.03	1.02	1.04	1.03	1.02	1.03	1.04
6	1.05	1.04	1.03	1.06	1.04	1.03	1.04	1.05
8	1.05	1.05	1.04	1.08	1.05	1.03	1.05	1.06
10	1.05	1.05	1.05	1.10	1.06	1.03	1.06	1.07

2.2.3 Age at First Egg

BFS achieved the highest theoretical response when applied to AFE, as illustrated in Figure 2.5. The progress did, however, appear to slow from about generation eight. FIS equalled the progress achieved with BFS up to generation three, but declined at a slower rate following generation three. IS, having the third highest response, improved at a constant rate up to generation six where it then levelled off. WFS produced the lowest response, being far below the other selection strategies. By generation 10, IS, BFS, WFS and FIS achieved a value 0.86, 0.81, 0.92 and 0.83 of the starting value of AFE, respectively, with SD's of 0.7, 1.2, 1.6 and 1.3, respectively.

The simulated method of IS produced a superior response when applied to AFE for the first five generations, but was overtaken by FIS for the following five generations. WFS improved at a greater rate than FIS initially, however the response weakened in generation four. Again BFS produced the lowest response, however, improvements were made at a constant rate showing no indication of levelling off and would most likely reach the levels of the other strategies soon after generation 10. By generation 10, IS, BFS, WFS and FIS achieved a value 0.87, 0.88, 0.87 and 0.86 of the initial value of AFE, respectively, with SD's of 0.9, 6.9, 1.5 and 1.8, respectively.

The theoretical and simulation methods of IS produced very similar responses, but the theoretical method was more efficient when using BFS and FIS. On the contrary, the simulation method was greater for WFS. BFS, for the theoretical method, and FIS, for the simulation method, produced the highest response and therefore successfully selected those birds reaching sexual maturity earliest, whereas WFS, for the theoretical method, and BFS, for the simulation method, produced the lowest response.
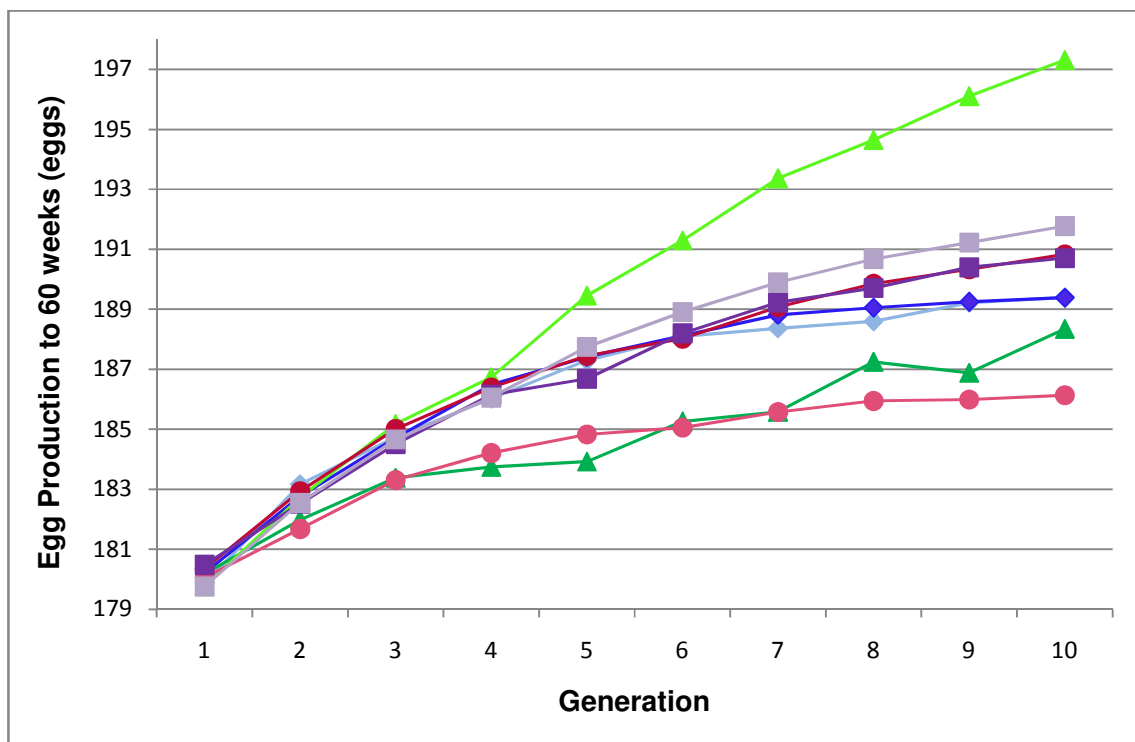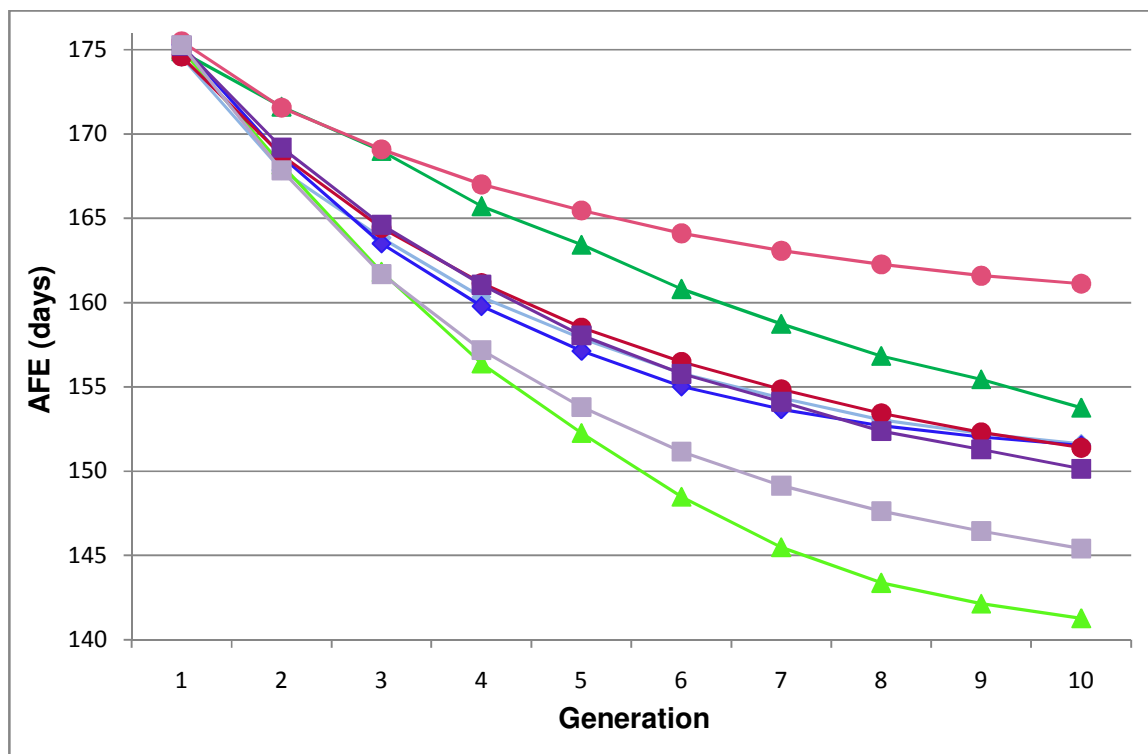

Figure 2.5   Comparison of simulated and theoretical selection techniques applied to the improvement of AFE (Individual Selection ⇨ ◆ Simulated ◆ Theoretical, Between Family Selection ⇨ ▲ Simulated ▲ Theoretical, Within Family Selection ⇨ ● Simulated ● Theoretical and Family-Index Selection ⇨ ■ Simulated ■ Theoretical)

Table 2.4   The change in AFE over ten generations of selection as a proportion of the initial value, using both simulated and theoretical methods of individual, between family, within family and family-index selection

Generation	Individual		Between Family		Within Family		Family-Index	
	Sim.	*Theor.*	*Sim.*	*Theor.*	*Sim.*	*Theor.*	*Sim.*	*Theor.*
2	0.96	0.96	0.98	0.96	0.97	0.98	0.97	0.96
4	0.92	0.91	0.95	0.89	0.92	0.95	0.92	0.90
6	0.89	0.88	0.92	0.85	0.90	0.94	0.89	0.86
8	0.88	0.87	0.90	0.82	0.88	0.92	0.87	0.84
10	0.87	0.86	0.88	0.81	0.87	0.92	0.86	0.83

2.2.4 Body Weight at 35 days

BFS yielded an impressive response when applied to the theoretical method of selection for body weight, as illustrated in Figure 2.6. The response was far superior to the other selection strategies and showed no sign of weakening in progress, even in generation 10, another illustration of the strategies' ability to preserve the SD of the trait under selection.   FIS followed, however a slowing in progress was evident from generation four. IS had an initial surge, but also faded in generation four and trailed far behind FIS in generation 10. WFS never reached the levels of the other strategies. By generation 10, IS, BFS, WFS and FIS achieved proportional increases of 1.15, 1.34, 1.11 and 1.21, respectively, with SD's of 6.2, 67.0, 19.0 and 18.0, respectively.

WFS and FIS produced similar results throughout the selection period when applied to the simulated method of selection for body weight. WFS was however slightly superior over most of the period.   IS increased at the same rate but dropped off in generation five.   BFS improved the value of body weight at an increasing rate throughout the selection period and would most likely reach the levels of the other strategies soon after generation 10.   By generation 10, IS, BFS, WFS and FIS resulted in a proportional increase of 1.15, 1.14, 1.17 and 1.17, respectively, with SD's of 8.0, 70.6, 17.2 and 15.5, respectively.

The simulated methods of WFS and IS resulted in greater progress than the theoretical method, whereas the theoretical methods of BFS and FIS were superior to the simulated methods. BFS, for the theoretical method, and WFS, for the simulation method, produced the highest response and therefore successfully selected birds with the heaviest body weight for 10 generations, whereas WFS, for the theoretical method, and BFS, for the simulation method, produced the lowest response.
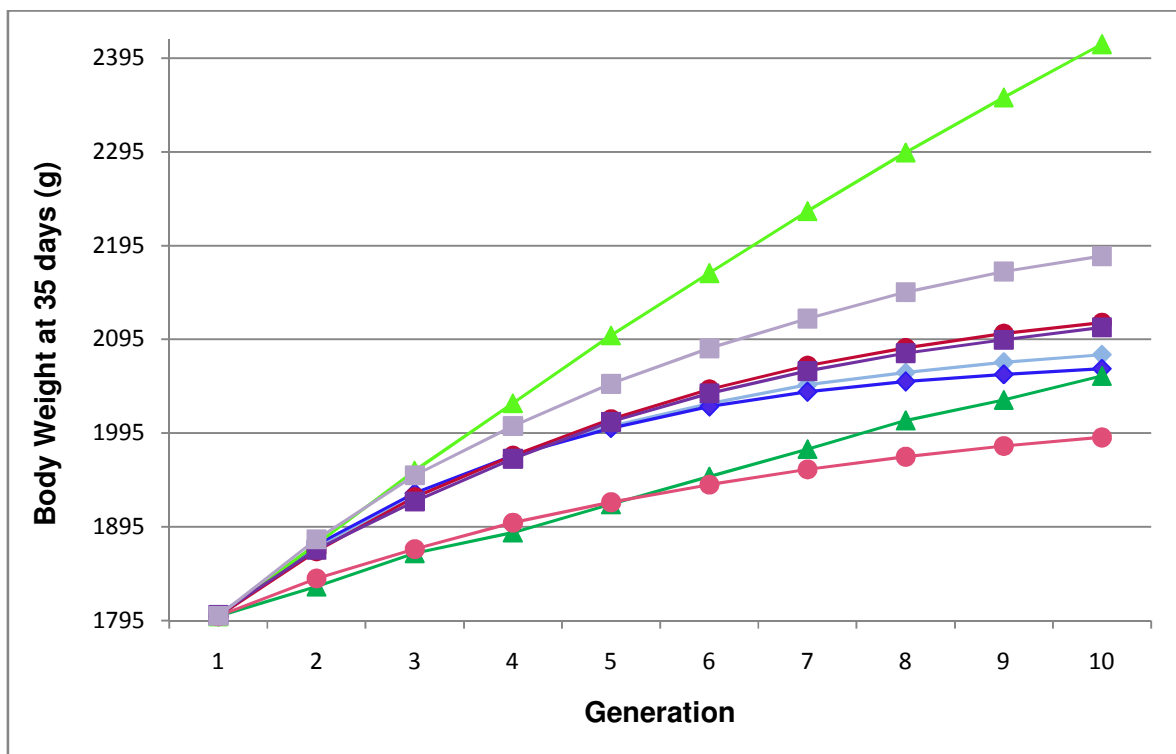
Figure 2.6 Comparison of simulated and theoretical selection techniques applied to the improvement of body weight at 35 days (Individual Selection ⇨ ◆ Simulated ◆ Theoretical, Between Family Selection ⇨ ▲ Simulated ▲ Theoretical, Within Family Selection ⇨ ● Simulated ● Theoretical and Family-Index Selection ⇨ ■ Simulated ■ Theoretical)

Table 2.5 The proportional increase in body weight at 35 days over ten generations of selection using both simulated and theoretical methods of individual, between family, within family and family-index selection

Generation	Individual		Between Family		Within Family		Family-Index	
	Sim.	*Theor.*	*Sim.*	*Theor.*	*Sim.*	*Theor.*	*Sim.*	*Theor.*
2	1.04	1.04	1.02	1.04	1.04	1.02	1.04	1.05
4	1.09	1.10	1.05	1.13	1.10	1.06	1.09	1.11
6	1.12	1.12	1.08	1.20	1.13	1.08	1.13	1.16
8	1.14	1.14	1.12	1.28	1.16	1.09	1.16	1.19
10	1.15	1.15	1.14	1.34	1.17	1.11	1.17	1.21

2.2.5 Body Weight and Egg Production

When the theoretical method of selection was applied to body weight, BFS had the largest negative effect on egg production, followed by FIS, IS and WFS. WFS affected the value of egg production markedly less than the other selection strategies. The simulation method of IS had the largest impact on egg production when body weight was selected. WFS and FIS followed closely behind, while BFS affected the value of egg production the least.

The theoretical procedure had a larger negative effect on egg production, when selection was applied to body weight, than the simulated procedure for all selection strategies.
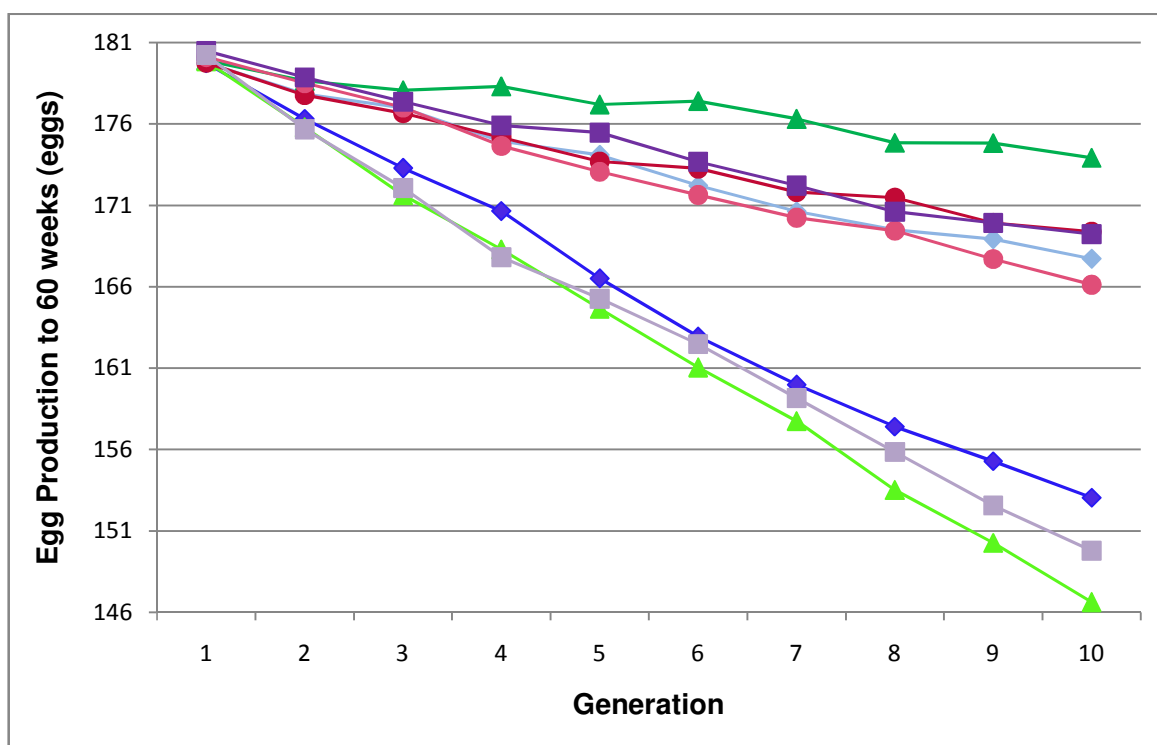
Figure 2.7 Comparison of effects of simulated and theoretical selection methods on egg production to 60 weeks when selecting for body weight at 35 days (Individual Selection ⇨ ◆ Simulated ◆ Theoretical, Between Family Selection ⇨ ▲ Simulated ▲ Theoretical, Within Family Selection ⇨ ● Simulated ● Theoretical and Family-Index Selection ⇨ ■ Simulated ■ Theoretical)

FIS had the largest negative impact on body weight when the theoretical method was used for direct selection of egg production. BFS and IS followed closely behind. Body weight deteriorated the least with WFS. When the simulated method of selection was applied to egg production, body weight deteriorated most rapidly with FIS, followed closely by WFS and IS. BFS affected the value of body weight markedly less.

The simulated method of selection for egg production had a larger negative effect on body weight than the theoretical method of IS, WFS and FIS. The theoretical method of BFS experienced a larger drop in body weight than the simulation method.
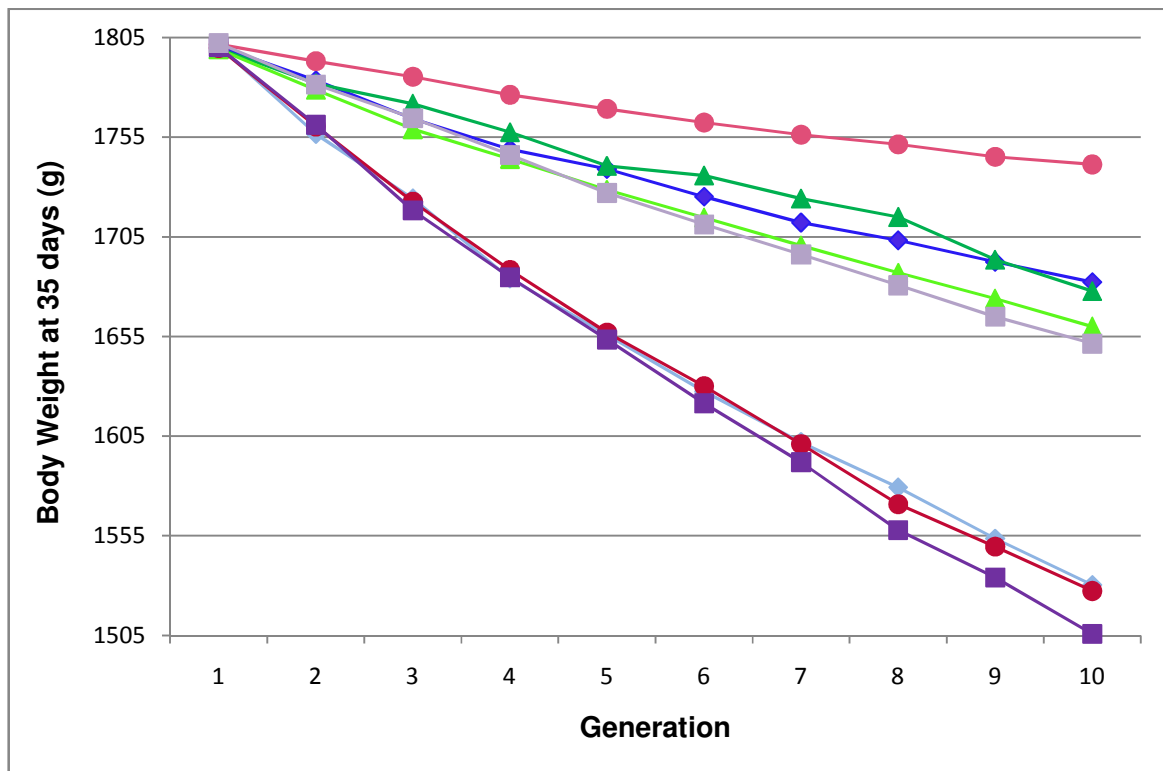
Figure 2.8 Comparison of effects of simulated and theoretical selection methods on body weight at 35 days when selecting for egg production to 60 weeks (Individual Selection ⇨ ◆ Simulated ◆ Theoretical, Between Family Selection ⇨ ▲ Simulated ▲ Theoretical, Within Family Selection ⇨ ● Simulated ● Theoretical and Family-Index Selection ⇨ ■ Simulated ■ Theoretical)

2.2.6 Correction Factor

Figures 2.9, 2.10 and 2.11 illustrate the results that were achieved using the family selection techniques and the correction factor. The response (added to the mean of the previous generation) in body weight at 35 days was plotted for the theoretical simulation models as well as the predicted results which were determined by multiplying the response achieved in IS to the correction factor (and adding the mean of the previous generation). These figures illustrate that the results achieved are in fact very similar.
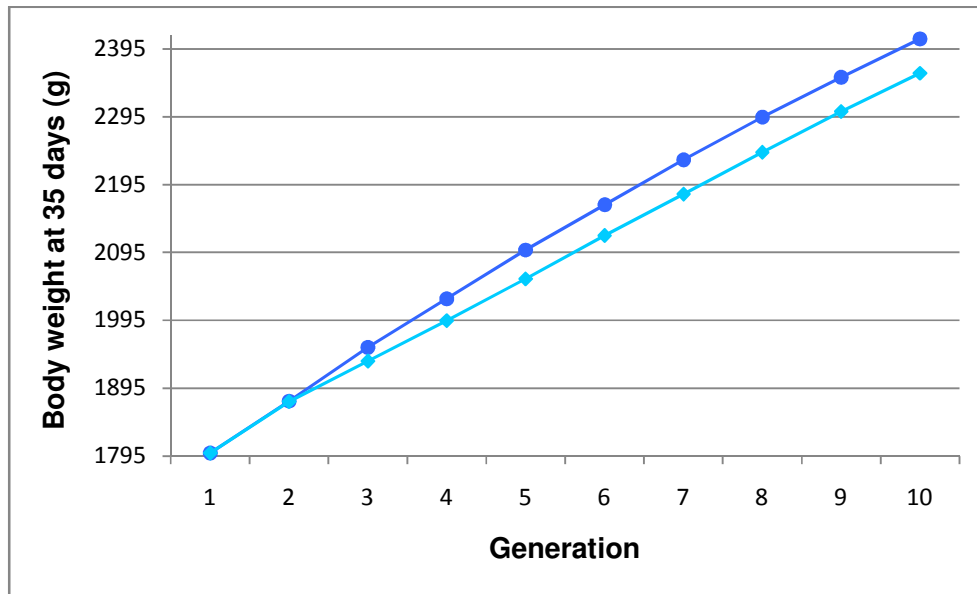
Figure 2.9 The response in body weight at 35 days over ten generations using the theoretical model and the correction factor for between family selection (● Model and ◆ Correction Factor)
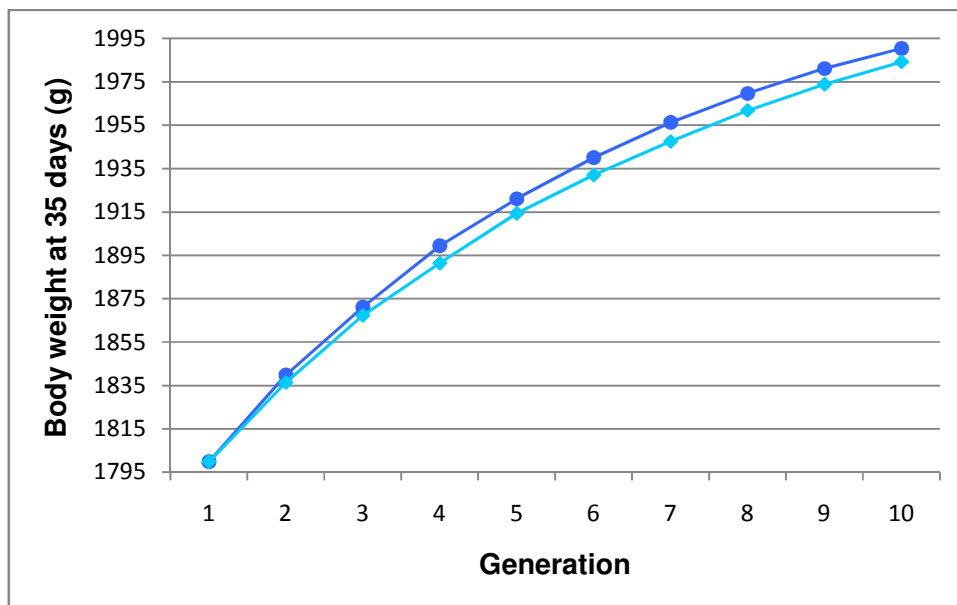
Figure 2.10 The response in body weight at 35 days over ten generations using the theoretical model and the correction factor for within family selection (● Model and ◆ Correction Factor)
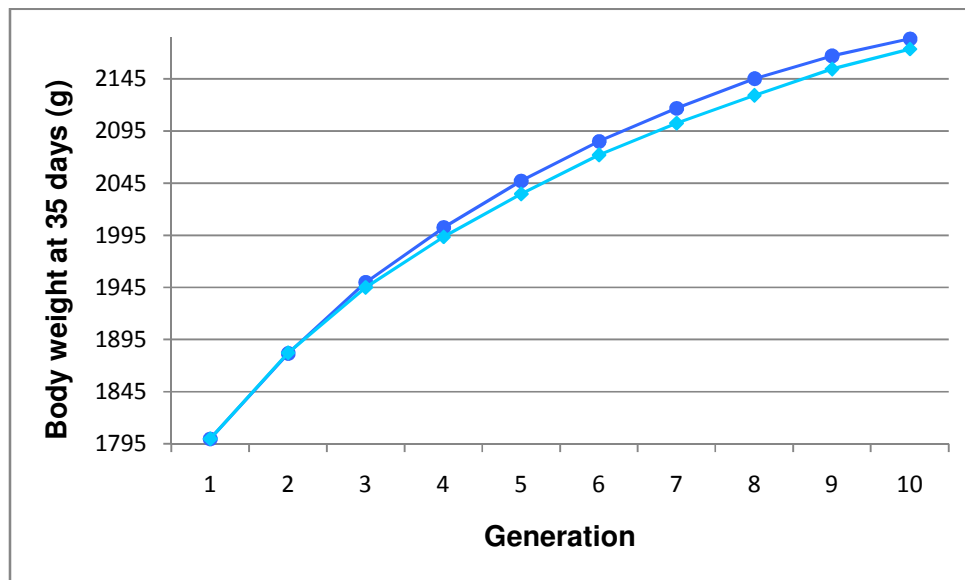
Figure 2.11 The response in body weight at 35 days over ten generations using the theoretical model and the correction factor for family-index selection (● Model and ◆ Correction Factor)

2.3 Discussion

The purpose of this chapter was to compare the performance of the four single trait selection strategies and to examine the results obtained when using the theoretical and simulation methods of predicting the responses to these selection strategies. The results of the theoretical method will be discussed first. As was earlier stated by Falconer & Mackay (1996), FIS should produce the best response when applied to any single trait. This was not the case in the present study, nor in the study of De Guisti (2003), in fact, FIS was not superior to any of the other selection categories. This result can be attributed to the inability of the strategy to maintain a reasonable SD throughout the selection period.

BFS was the victor for the theoretical method when applied to all four traits, but is notably superior to the other strategies when applied to egg production and body weight. The SD of egg production and body weight is far less affected when BFS is directed towards each of these traits. It was initially thought that the larger initial SD of these traits attributed to the increased success achieved with this strategy. However, the variation should be explained in terms of the CV, which is used to calculate the SD, yet this value is very similar for egg weight, AFE and body weight, disproving that the variation is responsible for the better performance of BFS when applied to egg production and body weight. A further possibility of differences in heritability were explored, however body weight and egg production possess heritabilities almost on either side of the spectrum, disproving this theory as well. Hence, it is not fully understood why BFS produces a noticeably superior response for egg production and body weight than with egg weight and AFE, but it is certain that BFS performs better than all other strategies for all traits due to the fact that it is more capable of maintaining the SD for all traits, hence allowing for selection amongst a larger range of values.

The reason for this result is rather simple, the SD is a factor in the response equation, therefore the larger the SD, the larger the response to selection will become. There are certain conditions under which FIS would prove superior, relating to the initial CV assigned to the traits. In this study the CV assigned to each of the traits was relatively low, depriving FIS of the large variation that it would use to its benefit to rapidly increase the value of the trait under selection. When a large CV was used for the traits, in a previous exercise, FIS caused the limit for most traits to be reached rapidly and was therefore the superior strategy in all cases. However, in achieving this goal virtually no variation in the trait remained.

The CV of the population gives an indication of the extent to which genetic selection might be successfully applied, with higher CV's indicating a wider range of values between the mean and the best (or worst) individuals. As selection proceeds, the variation in the population is reduced, simultaneously reducing the difference between the mean of the population and those individuals exhibiting superiority for the particular trait. In this way a ceiling is reached as the better individuals display values closer and closer to the mean of the population. This may not be the case in the real situation as the environment or management procedures would introduce additional variation. But, of greater importance, is the observation that after about 15 generations of selection for a given trait spontaneous increases in variation occur, probably as a result of mutations, which lead to a new surge in potential gains through selection (Dudley & Lambert, 2004). In addition, Liu *et al.* (1994) discussed the occurrence of an irregular response or "waves of response" that may occur in short or long-term selection experiments. They described this as a sudden increase in response that is followed by a cessation in the response. Their explanation was based on the population's increased sensitivity to micro-environmental factors due to the intense selection they had been exposed to for so many generations.

In practice, maintaining a satisfactory degree of variation is imperative. "A selection method that retains the variation in the population for longer periods of time such as between family selection and within family selection, to a lesser degree, will produce better responses to selection in later generations" (De Guisti, 2003). Thus, the progress of a trait must be monitored and if advancements are made rapidly, the selection pressure should be removed for a few generations, allowing the genetic variation of the trait to return to satisfactory levels, during which time selection could be applied to a correlated trait.

IS was the third best strategy, using the theoretical method, in all cases, therefore WFS produced the weakest response. IS and WFS reduced the SD of all traits relatively rapidly, preventing these from making any significant progress. A further explanation as to why WFS made the least progress, is that environmental effects were not taken into account by the models (De Guisti, 2003). WFS is most effective when a large component of environmental variance is common to members of a family (Falconer, 1981). Because environmental effects were not taken into account by these models, WFS no longer had an advantage over the other selection techniques and thus made the least progress. It is possible to simulate different environments in the same way the population was simulated in the current study;

hence it may be worth examining the selection strategies further under differing environmental conditions.

The considerable superiority of BFS over the other strategies, when using the theoretical method, is surprising, but nevertheless can be explained. Entire families are selected as parents for the following generation with BFS, whereas individuals are chosen as parents when using IS. Members of the family may be exceptional, moderate or below average, therefore a range of individuals become parents of the next generation boosting the SD. The strategy is capable of more progress given the wider range of individuals to choose from. This situation does however illustrate the problems and limitations that may arise from using the simulation models. It was previously mentioned that the method for BFS results in a large reduction in genetic variance, consequently the rate of inbreeding is greatly increased (Falconer & Mackay, 1996). However, the model is unable to account for this loss in genetic variability and consequent increase in inbreeding, thereby inflating the success and progress of BFS.

The results for the simulation method differ from the theoretical method. With this method, the effect of the SD boosting the response is removed since the response equation is not used. Therefore, BFS generates the weakest response. This result would be expected since a proportion of the individuals selected as parents for the next generation are below average and would reduce the response. However, as discussed above, this maintains a decent SD allowing the selection period to continue for a longer period. This is illustrated in the results for the simulation method, as the values increase gradually, however experience a constant improvement, which will undoubtedly result in BFS surpassing all of the remaining strategies soon after generation 10. Thus, it can be argued that BFS is the most successful strategy when using the simulation method, depending on the criteria. If a rapid improvement is required, WFS, FIS or IS should be used.

WFS, FIS and IS produced very similar responses when the simulation method was used, a sharp initial increase followed by a deceleration at approximately generation five. IS and FIS were superior when applied to AFE, WFS was superior when applied to body weight, WFS and FIS produced a very similar response when applied to egg production, and IS was superior when applied to egg weight.

Mention must be made of the advantages to indirect selection for a positively correlated trait. The theoretical and simulation methods of IS produced the largest response in egg production, when selection was applied to AFE, and in body weight, when selection was applied to egg weight. For the simulation method, the value for body weight when indirectly selected through egg weight, was only 113 g below the value achieved when direct selection was applied to body weight. Of greater benefit is the comparison in SD for body weight, which is 72.2 under indirect selection and 8.0 under direct selection. For the theoretical method, the value for body weight when indirectly selected through egg weight, was only 82 g below the value achieved when direct selection was applied to body weight. Furthermore, the SD for body weight was 100.6 for indirect selection and 6.2 for direct selection. Indirect selection for egg production, with the simulation method, resulted in the same number of eggs in comparison to direct selection for egg production, but the SD for indirect selection was 11.9 and only 1.3 with direct selection. For the theoretical method, the value for egg production when indirectly selected through AFE was seven eggs above the value achieved when direct selection was applied to egg production. Furthermore, the SD for egg production was 9.0 for indirect selection and 1.0 for direct selection. This illustrates the value of indirect selection for favourable traits. The response in the correlated traits to selection in this study are similar to those reported by Poggenpoel *et al.* (1996) and Sharma (1998).

When selecting for body weight with the theoretical method, BFS, FIS and IS had a large impact on egg production, WFS had the least effect. BFS, FIS and IS are the strategies making the most progress in body weight, hence they cause the most disruption to the value of egg production. Similarly, when selecting for body weight with the simulation method, IS, WFS and FIS negatively affected egg production, whereas BFS caused the least disruption. Again, this is in line with the relative progress achieved in each selection strategy. Similar results were found with the theoretical and simulation methods in body weight when selection was applied to egg production. This demonstrates what has occurred, and continues to occur in the industry today. A large amount of progress is made with growth traits, however, it is at the cost of the reproductive traits. The dedication of the industry will continue to lie with growth traits since it has been proven that in an integrated broiler enterprise the economic return of selection for reproductive traits is much smaller than that for production traits (Jiang *et al.*, 1998). However, the selection technique used by certain breeding companies is dependent upon the objectives of the breeder. Dominant breeding companies can afford to

place more emphasis on growth traits (Hunton, 1990), whereas, breeders with minor market share must attempt to increase body weight whilst maintaining egg production.

It is obvious that large responses made in each trait do come at a price. However, in the simulation method, implementing BFS would prove advantageous to growth traits and have the benefit of minimising the negative effects on reproductive traits and reducing the amount of stress that is placed on the birds. Furthermore, family selection techniques are critical in preventing a loss of fitness and reproductive ability to the breeding stock. It is at the discretion of the breeder to decide whether the value of certain traits should be sacrificed in order to achieve an improvement in another, or implement a strategy that will allow for lesser improvement in both traits.

The theoretical method had a larger negative effect on egg production, and the simulation method had a larger negative effect on body weight when selection was directed towards body weight and egg production, respectively. This helps to gain some insight into the technique used in each of the methods. The heritability of the trait has a greater impact on the progress of the traits in the simulation than the theoretical method. The heritability is used in the response equation of the theoretical method, however its effect is minimised when multiplied by the other factors needing consideration. Therefore, when selection is applied to body weight and the response in egg production is examined, the simulated method would generate a lower impact on egg production since it possesses a poor heritability and any selection directed towards or against this trait would not produce such a significant reaction than if compared to a trait with a high heritability. Conversely, if selection is applied to egg production and the correlated response in body weight is of interest, the simulated method would have a more significant impact since body weight possesses a high heritability and any instruction directed towards this trait is received and largely inherited by the offspring.

Egg production, possessing a high CV, has the potential to achieve a large amount of progress due to the increased possibility of more individuals positioned far above the mean. However, since the trait is easily influenced by the environment, it is possible that the expression of the trait is due to a favourable environment hence reducing the chance of it being passed on. It is thus difficult to achieve a large amount of progress in egg production or traits exhibiting a low heritability.

This leads onto the question which must be asked, why do the theoretical and simulation methods produce results that are so different? Essentially, the simulation method differs from the theoretical method since it eliminates the response equation. Thus the true ability of the strategy, and the simulated population of birds, is expressed and not suppressed by the response equation. The theoretical method certainly serves its purpose when a simulated population of birds is unavailable, however, the selection strategies are better modelled and their principles demonstrated using the simulated method.

A likely reason for the difference in results between the two methods is that with the theoretical method a large population response is being predicted, whereas with the simulation method only a small sample population is being used, which may not fully represent the population from which it came. If this exercise were repeated with a population size of 50 000 instead of 500, the differences that exist are most likely to be less.

Although larger population sizes are likely to close the gap in results between the theoretical and simulation methods, various other contributing factors may also exist. The theoretical and simulation methods for IS are very similar, the theoretical method generating a larger response when applied to BFS and FIS, although the difference was not as large in FIS, and the simulation method generating a larger response when applied to WFS.

It is logical that the theoretical and simulation methods would yield similar results for IS as the response equation for IS is at its simplest: it is in the family selection techniques that more complex factors are introduced. The intensity and SD are accounted for in the selection process with the simulation method, and the heritability is used to determine the response, hence naturally mimicking the response equation.

The differences displayed between the theoretical and simulation methods for the family selection techniques may be attributed to the extra factor included in the response equation, the relevant heritability values. It was decided that the true heritability of each trait would be used for the simulation method to avoid any inconsistencies that may disrupt the true performance when this strategy was used. Upon deliberation, two reasons for the differences are proposed. Firstly, the genetic gains were better when the theoretical method of BFS and FIS was used, possibly due to the inflated measure of heritability used with this method. This inflated heritability value is used in the response equation each generation, resulting in a

greater than expected response. The converse is true for WFS. The within family heritability value is much lower than the original heritability value, which reduces the resulting response to selection each generation. The reason for the lowered heritability value for WFS is the lower t value, or correlation between members of families, used to calculate the heritability. WFS results in a greater deviation between family members, reducing the correlation between family members or the t value. The method of calculating heritability also affects the resulting value. Therefore, the response equation enhances genetic progress when using BFS and FIS, and reduces this with WFS.

Another explanation for the difference in response of the theoretical and simulation method for the family selection techniques is the family size. Although a family size of five was used for the theoretical method, the response equation reverts the response to selection back to theoretical methodology. It is possible that if the family size used in the simulation method were increased, that the response to the family selection techniques of the simulation method would closer represent those of the theoretical method.

The simulation method results are specific to the simulated population of 500 birds that were randomly generated each generation and could not be extrapolated for a larger sample size. The theoretical method is most likely to represent the results that would be obtained from a larger population. Thus, it cannot be said whether the simulated method is superior to the theoretical method, or is capable of presenting a more accurate representation of the true ability of the selection strategies.

The results obtained by multiplying the response to selection for IS by the correction factors for BFS, WFS and FIS indicate a close similarity to the results from the theoretical simulation models. This indicates that the theoretical simulation models have provided results that are accurate under the circumstances which they were performed.

2.4 Conclusion

Single trait selection has proved capable of improving the value of both the selected trait and those with which the trait is positively correlated. However, negatively correlated traits suffer under this method of selection, which may seriously reduce the commercial value of the resultant stock. The simulated and theoretical methods of single trait selection produced differing results as BFS was superior when applied to the theoretical method while WFS produced the weakest response, whereas the opposite was true for the simulated method. Various explanations as to why these methods produced varying responses have been proposed, however, the simulated method most likely provided a more accurate representation of the response to selection of the population of 500 birds that were simulated in each method.

An alternative strategy to single trait selection is to construct an index based on the GEV of each trait and to select individuals on the basis of their resultant index values. It is possible to make use of such an index to evaluate the overall economic progress made by selection for single traits, and such a comparison will be made once the method for Index Selection has been described and used for multiple trait selection in a simulated population. The relative efficiencies of single (simulated method) and multiple trait selection will be compared.

CHAPTER 3
ECONOMIC VALUES AND MULTIPLE TRAIT SELECTION

3.1 Economic Value: Introduction and Motivation

In the previous chapter the consequences of single trait selection in a broiler population were reported. It was recommended there that multiple trait selection would be more advantageous in the case where two important economic traits are negatively correlated, as is the case in the broiler industry. But for multiple trait selection to be of any value the economic values (EV) of the various selection traits must be known and used in the selection index. In this chapter, the economic evaluation of a number of important traits in broiler production are described prior to evaluating the genetic progress that can be made with the use of a selection index applied to multiple trait selection.

 A model was thus developed for the economic evaluation and EV derivation of the various economically important production parameters in the broiler industry. This model calculates the influence of production parameters and costs, involved in producing the final product, on overall profitability. The intention of this study was to calculate the EV of the economically important traits in broiler production. These were considered to be egg production, age at first egg (AFE), fertility and hatchability of the breeder hens, and mortality, body weight and feed conversion (FC) of the broilers. The reason for selecting the above traits is due to their obvious impact on the income of an operation.

The production stages that were considered included the breeder rearing and laying farm, the broiler hatchery, the broiler farm and the processing plant. This study was limited to the above stages as the traits considered critical for meat production can be defined as those relating to reproductive performance of the dam and those concerning growth and carcass characteristics of the progeny (Moav & Moav, 1966; Smith, 1964). Furthermore, Jiang *et al.* (1998) reiterated the importance of considering the whole production-marketing system (as stated by Dickerson, (1970)), and limited their study to the above production stages. Groen *et al.* (1998) also focused their study on the above stages. A questionnaire was compiled for farmers from each sector to complete. In each case an attempt was made to interview more

than one representative from each sector as realistic figures are required for the model. Not all figures obtained were used in the calculation of the cost and revenue EV's, but they served in the overall economic evaluation of the broiler industry.

Similarly to the calculation of the cost EV's in this study, Shalev & Pasternak (1983), Pasternak *et al.* (1986) and de Vries (1989) agreed that an improvement in the performance of the birds does not result in a change in the quantity of output, but rather a change in the cost; the cost per unit product is reduced. For example, any improvement in egg production, fertility or hatchability will reduce the number of breeder hens required to produce a fixed number of chicks, thereby reducing chick production costs. An improvement in broiler weight will shorten the growth period, consequently reducing the rearing costs. Spears *et al.* (1990) declared that the most efficient unit for assessing the performance of a poultry producer is cost per kilogram produced.

This method was followed based on the conditions proposed by Smith *et al.* (1986) on deriving economic weights. The authors state that any change in production achieved should not be represented by the change in profit, since extra profit is simply achieved by rescaling the size of the operation, hence no genetic change is required. Smith *et al.* (1986) reiterated the importance of including only the saving in cost per unit of product when determining the economic weightings.

Akbar *et al.* (1986) developed their own formula describing profit per individual production unit, alternatively known as a profit function. The authors stated that the bioeconomic objective of the operation could be set as the improvement of the profit function and is dependent on the aim of the researchers. After all, the EV of a trait is defined as the increase in profit per unit improvement of the trait (Hogsett & Nordskog, 1958). Jiang *et al.* (1998) utilised a deterministic economic model, developed by Groen *et al.* (1998), based on profit equations, with a fixed broiler meat output, to derive their EV's in broiler breeding. Changes to either the cost or profit of the production system were used to determine the levels of the EV's. Groen (1988) and Hogsett & Nordskog (1958) also considered both costs and profit when calculating their EV's.

Jiang *et al.* (1998) raised a very important point about the derivation of EV's for non-integrated and integrated enterprises. For a non-integrated system, the basis for evaluation

is the profit margin, the difference between revenue and cost. The cost price per unit of product is used as the basis for the integrated system. Thus the EV's are determined by calculating the profit margin (non-integrated) or cost price (integrated) at a starting point followed by an incremental improvement in the given trait. Both systems, however, derive the EV's from a saving in cost rather than an increase in output. As was adhered to in the present study, one set of EV's was determined based solely on the effect of an improvement in a trait on the cost to produce that trait. The other set of EV's were determined based on the influence an improvement in a certain trait will have on the revenue and cost to produce the further improvement. However, in both cases focus is placed on a saving in cost rather than an increase in output and hence profit. Thus it can be said that the EV's in the present study are representative of those from a non-integrated and integrated enterprise based on the definition given by Jiang *et al.* (1998).

The aim of this exercise is to determine the relative importance of each of the chosen traits to the economics of a broiler operation. It is best to examine the results of previous studies, one of which was performed by Strain and Nordskog (1962b) involving data taken from the Maine Random Sample Broiler and Production Test, and illustrated that broiler weight and broiler FC had the most significant impact on net income. The same study demonstrated the relative insignificance of egg production in the parent flock. Similarly, Pasternak *et al.* (1986) determined the contribution of various economically important traits to economic gains in the turkey industry. Food utilisation comprised 15.1% of the economic gain, while egg production claimed only 3.7% and turkey mortality, fertility and hatchability contributed very little to economic gains with values between 0.4 and 0.7%. The giant to the industry, known as growth rate, contributed a staggering 77.8%, illustrating that it is indeed the most important trait in the integrated turkey enterprise. Growth traits combined (food utilisation, reduced body fat content and growth rate) had the most important economic implications, contributing 95.2% to the turkey enterprise, while reproductive traits and mortality were of much less EV. Furthermore, Jiang *et al.* (1998) found that the economic return of selection for reproductive traits is much smaller than those of production traits in an integrated broiler enterprise.

A similar study performed by Shalev & Pasternak (1983) examined the potential economic saving of production costs by certain economically important traits in an integrated broiler operation. The authors found that growth rate and food utilisation share similar EV's and represent 94.3% of the annual potential economic saving in production costs. Selection for

increased egg production represented only 4.2%, and selection for fertility, hatchability and reduced mortality accounted for less than 1% each.

Pollock (1999) determined the value of an improvement to the performance of certain traits in an American Broiler Primary Breeder Company (BPBC). The weekly value of a one percent increase in hatchability, eviscerated carcass weight and FCR was $30 000, $385 000 and $130 000 respectively. The benefit of improvement to growth traits exceeds the benefit of improvement to reproductive traits by a factor of between 4 to >11. For this reason, breeders of the broiler industry will continue to focus on growth traits. The emphasis placed on selection for reproductive traits by BPBC is dependent on customer feedback and competitive performance of other broiler companies. Much hope is invested in the phenotype of the bird and that it may still be manipulated to counteract, or minimise, the genetic losses that have occurred in the reproductive efficiency of the bird, when the need arises.

Realistically, egg production is of very little value to the broiler industry as the objective of the industry is to maximise meat production. The fastest method of achieving maximum meat production is by improving growth rate of the broilers by genetic selection. It just so happens that selection for egg production compromises the improvement in growth rate, making it second to growth rate and growth traits that would positively influence the expression of growth. However, if these meat producers don't hatch, they will not be able to reach their full potential. If egg production levels were allowed to drop, this trait would surely have an effect on the net income or economic gains of an operation. The relative values of broiler meat and eggs will differ depending on the current situation; if too few eggs are available in a period of high demand for broiler meat, the value of eggs will increase considerably.

Moav & Moav (1966) summarised their study focusing on the relative value of fertility traits and efficiency of meat production in the evaluation of the economic merit of breeding stock, demonstrating the difficulty in making a defined choice. They treated demand independently of the performance of the breeders when evaluating the broiler progeny economic merit. Naturally the EV for improvement of fertility traits is comparatively lower than if the demand were determined by the reproductive performance of the parents. This case would rarely occur, excepting evaluation of a breeding stock for a non-integrated hatchery. Demand would normally be considered independent of reproductive traits for integrated operations and is thus the more realistic option, showing the importance of meat traits relative to reproductive

traits as influencers of the final profit achieved. Difficulties arise in the non-integrated enterprise as the economic merit of breeding stock clearly differs between the hatchery manager and the broiler grower due to their differing objectives. However, Moav & Moav (1966) suggest that the poultry breeder base future breeding stock evaluation on the position of the integrated enterprise which places more emphasis on broiler traits. However, the authors also highlighted the importance of maintaining a satisfactory level of reproductive performance of the parent stock for the hatchery managers.

By definition, the EV of a trait is "the change in profitability of an enterprise expressed per unit product output as a consequence of one unit of change in performance of the trait considered, without changing performance of other traits" (Jiang *et al.*, 1998). The unit product output would be a broiler egg for the breeder farm, a broiler chick for the hatchery, and a marketable broiler for the broiler farm and the processor. The unit of change in performance of the economically important traits in the case of this study is defined as an additional chick per hen for egg production, bringing the birds into lay a day earlier for AFE, an extra percent fertility and hatchability for fertility and hatchability respectively, a one bird reduction in mortality for mortality, reaching target body weight a day earlier for body weight, reducing FCR by a day of feed intake for FCR and an extra gram of egg weight for egg weight.

3.1.1 Materials and Methods

The economic model was developed in Microsoft Excel. It does not include all costs at each stage of production, only those that were considered significant and which impact directly on the final product. Furthermore, in calculating what a trait is worth, or the EV, the costs that are incurred in generating that trait, and the money that is made from the certain trait, need to be considered. Similarly to the study performed by Strain and Nordskog (1962a), the emphasis of this model is not in the profit potential of a broiler enterprise, but the effect that various production factors have on profit potential. Thus, gross income and total costs were expressed for each production cycle. The model can be applied to both a non-integrated and integrated operation.

Model construction will be discussed below.

3.1.1.1 Breeder Farm – Rearing

A new worksheet was created and named Breeder farm – Rearing. Basic flock information was required to be used in calculating R/bird and R/flock figures. This included number of males and females per house, length of period in house, length of cleanout time and cycles per year. The costs were split into fixed and variable costs. Fixed costs are those required for running the operation (Smith *et al.*, 1986) and are incurred regardless of whether the birds are present or not, and do not change with bird age (Reece & Lott, 1984) or killing age (Dyfri Jones, 1962). These included maintenance, salaries and wages, and depreciation. Depreciation was calculated as 20% of building costs. The units used for fixed costs were R/annum. Total fixed cost was calculated as the sum of all fixed costs in the units R/flock and R/bird. Variable costs are usually associated with the individual animal (Smith *et al.*, 1986) and are those incurred when the birds are present and in production and vary with the killing age of the birds (Dyfri Jones, 1962). These included feed costs, electricity, water, vaccination, shavings, price of day-old breeders, gas and cleaning of house. The total amount of feed consumed by each bird for that period was taken as an average between male and female feed intakes. This figure was used to calculate the total feed costs, a very important yet erratic cost to any animal producing operation. The units used for variable costs were R/flock and R/bird. Total variable cost was calculated as the sum of all variable costs in the units R/flock and R/bird.

The total cost of rearing to 21 weeks per flock and per bird was then calculated excluding and including mortalities, culls and sex errors. A significant number of birds are lost each cycle due to mortalities, culling (as only the superior birds are chosen for the laying farm) and sex errors made by the supplying company. Therefore it is necessary to determine the costs of the rearing farm inclusive of mortalities, culls and sex errors in order to obtain a cost that is more representative of the true value. Accounting for these costs will essentially represent a saving of money, as these birds will no longer be fed, thus feed costs will be reduced. However, they also represent an increase in the per bird cost, as the final cost will be divided by fewer birds, thus increasing the per bird cost. It was assumed that the majority of these fatalities occurred midway through the rearing period, if not, some would have occurred at the beginning, and others near the end, so the birds would only have consumed half of the amount of feed required for the rearing period. Therefore, the cost of a bird that had died, been culled or had a sex error was calculated by halving the feed costs and multiplying this by the total number of mortalities, culls and sex errors. This was subtracted from the initial cost of rearing to 21 weeks per flock. In order to calculate the cost of rearing to 21 weeks per bird (accounting for mortalities, culls and sex errors), the cost of rearing to 21 weeks per flock (accounting for mortalities, culls and sex errors) was divided by the number of males and females left at the end of the rearing period.

Production records were recorded for males and females separately and used in further calculations. These included mortalities, culls and sex errors over the 21 week period for both males and females. The number of males and females left at the end of the 21 week period was also calculated to enter into the laying farm.

The only significant income during the rearing period, other than for the birds sold at the end of the period, was for litter and culls sold. The total income per flock and per bird was calculated. These small values were subtracted from the total costs including mortalities, culls and sex errors, resulting in the total costs per flock and per bird for the rearing farm.

3.1.1.2 Breeder Farm – Laying

A new worksheet was created and named Breeder farm – Laying. Basic flock information was required to be used in calculations for the worksheet. This included number of males and females per house, length of period in house, length of cleanout time, cycles per year,

age at photostimulation and body weight at 20 weeks. The costs were also split into fixed and variable costs. Fixed costs (units in R/annum) included maintenance, salaries and wages, and depreciation. Depreciation was calculated as 20% of building costs. Total fixed costs was calculated as the sum of all fixed costs in the units R/flock and R/bird. Variable costs (units in R/flock and R/bird) included feed costs, electricity, water, vaccination, shavings, hen depreciation, cleaning of house and cost of 21 week old pullet. In order to calculate the feed costs per bird, the total intake of a bird on each ration must be known. Given the records of a flock of birds, the average intake can be calculated in a similar way to that done on the worksheet labelled "Calc of b1 & b2". Hen depreciation represents the loss in value of the hen as it ages. It is calculated as the cost to purchase a flock of 21 week old pullets subtracted from the value that the birds are sold for at the end of their production period added to the amount made from culls throughout the production period. Total variable costs was calculated as the subtraction of hen depreciation from the sum of all variable costs, excluding the cost of 21 week old pullets, as it was used in the calculation of hen depreciation. Hen depreciation was subtracted from the variable costs as it can represent an income if the value of the bird at the end of the production phase is higher than at the beginning of the production phase. Total variable costs was calculated in the units R/flock and R/bird.

Total fixed and variable costs were then summed to give a cost of production for 41 weeks, excluding culls and mortalities. Since the number of mortalities and culls is significant, these figures must be taken into account. The most important saving of costs with the dead and culled birds is the feeding costs. Yet again it was assumed that the majority of these fatalities occurred midway through the production period, therefore the birds would only have consumed half the amount of feed required for the full production period. Thus, half the feeding costs were multiplied by the total number of mortalities and culls, and this was subtracted from the initial cost of production for 41 weeks per flock, excluding culls and mortalities. In order to calculate the cost of production for 41 weeks per bird (accounting for culls and mortalities), the cost of production for 41 weeks per flock (accounting for culls and mortalities) was divided by the number of birds left at the end of the production period.

Production records representing the productivity of the flock were recorded in the worksheet. They included the percentage of females to males, the productivity of the farm, the settable egg percentage and the percentage of mortalities and culls over the 41 week period.

Calculations were completed to determine AFE, the total, settable and reject eggs per hen, the total number of mortalities and culls and the number of birds left at the end of the 62 weeks. The following equation from Lewis *et al.* (2007) was used to calculate AFE:

$$AFE = 414.15 - 2.558 \times (A) + 0.00937 \times (A^2) - 0.02268 \times (BW)$$

Age (days) at photostimulation   (A)
Body Weight (g) at 20 weeks   (BW)

A linear equation was used to calculate the number of eggs per hen. Inputs to the equation included the productivity of the farm and the AFE. The number of settable and reject eggs per hen was calculated from the percentage of settable eggs. The number of birds left at the end of the 62 week period was calculated by subtracting the total number of mortalities and culls from the number of birds entering the house at the beginning of the laying period.

The income already discussed is that from the birds sold at the end of the production period, and from birds culled throughout the production period. Since these values were used in the hen depreciation calculation, they were not considered for the total income calculation. The only commodities considered were litter, reject and settable eggs. For reject and settable eggs, the number of hens at the beginning of the laying cycle could not be used to calculate the income per flock, due to the mortalities and culls that occurred. Some of the culled and dead birds would, however, have laid eggs, hence it was assumed that half the number of these birds did not lay eggs, which were subtracted from the remaining birds. The total income per flock and per bird housed, and the profit per flock and per bird was calculated for the laying house. In order to investigate the effect of increasing the number of eggs per hen, the cost and income per settable egg was calculated. This was simply done by dividing the cost or income by the number of settable eggs.

3.1.1.3 Broiler Hatchery

A new worksheet was created and named Broiler Hatchery. Basic flock information was required to be used in calculations for the worksheet. This included the egg capacity per annum and price of broiler hatching eggs/dozen. The costs were also split into fixed and variable costs. Fixed costs (units in R/annum) included maintenance, salaries and wages,

and depreciation. Depreciation was calculated as 20% of building costs. Variable costs (units in R/annum) included electricity, water, vaccination, distribution, packaging and cleaning costs. The cost of eggs per week was also included in the variable costs. Total fixed and variable costs was calculated as the sum of all fixed and all variable costs in the units R/week and R/chick. In order to convert the units from R/annum to R/week, the sum of all fixed and variable costs was divided by 52 weeks. For calculation of the total fixed and variable costs in the units R/chick, the total fixed and variable costs in R/week were divided by the number of A-grade chicks sold per week, this being calculated under the production records for the broiler hatchery. The final cost per A-grade chick sold was simply the sum of the total fixed and variable costs per chick.

Production records representing the productivity of the flock were recorded in the worksheet. They included the percent reject eggs, fertility, hatchability of fertile eggs and downgrades. Calculations were completed to determine the weekly value of reject eggs, fertile eggs, hatching chicks and downgrades. From these figures the number of A-grade chicks sold per week was calculated.

The main source of income from the broiler hatchery is sale of A-grade chicks, reject eggs and downgrades. These commodities were summed to determine the total income per chick. The cost per A-grade chick sold was then subtracted from the total income per chick to give the total profit.

3.1.1.4 Broiler Farm

A new worksheet was created and named Broiler Farm. Basic flock information was required to be used in calculations for the worksheet. This included number of day-old chicks purchased per week and the cost of a day-old broiler. The costs were also split into fixed and variable costs. Fixed costs (units in R/annum) included maintenance, salaries and wages, and depreciation. Depreciation was calculated as 20% of building costs. Variable costs (units in R/annum and R/bird) included feed costs, electricity, water, vaccination, shavings, gas, cleaning of house and cost of day-old broiler. Total fixed and variable costs was calculated as the sum of all fixed and all variable costs in the units R/week and R/bird. In order to convert the units from R/annum to R/week, the sum of all fixed and variable costs were divided by 52 weeks; in the case of variable costs the values with units in R/bird were

multiplied by the number of day-old chicks purchased per week. In order to calculate the total fixed and variable costs in the units R/bird, the total fixed and variable costs in R/week was divided by the number of day-old chicks purchased per week.

Total fixed and variable costs were then summed to give a cost of production per week and per bird, excluding culls and mortalities. Since the number of mortalities and culls is significant, these figures must be taken into account. The most important saving of costs with the dead and culled birds is the feeding costs. Again it was assumed that the majority of these fatalities occurred midway through the production period, so the birds would only have consumed half the amount of feed required for the full production period. Thus, half the feeding costs were multiplied by the total number of mortalities and culls, and this was subtracted from the initial cost of production per week, excluding culls and mortalities. In order to calculate the cost of production per bird (accounting for culls and mortalities), the cost of production per week (accounting for culls and mortalities) was divided by the number of birds sold per week. The cost of production per kilogram (accounting for culls and mortalities) was calculated as the cost of production per bird (accounting for culls and mortalities) divided by the final body weight of the bird.

Production records representing the productivity of the flock were also recorded in the worksheet. They included final body weight, mortality and culls. Differences exist between male and female birds, these include early and late mortality, feed consumption, finishing weight and price per kilogram of live weight at finishing (Groen *et al.*, 1998). However, an average value was obtained for these figures. Calculations were completed to determine the total feed intake per bird, the FCR and the total mortalities and culls per week. From these figures the number of birds sold per week was calculated.

The main source of income from the broiler farm is the sale of the finished and culled birds and the litter. These commodities were summed to determine the total income per week, per bird and per kilogram. The cost of production per week, per bird and per kilogram was then subtracted from the income per week, per bird and per kilogram, respectively, to give the profit per week, per bird and per kilogram.

3.1.1.5 Processing

A new worksheet was created and named Processing. Basic information was required to be used in calculations for the worksheet. This included number of live birds entering the abattoir per week and the cost of a live broiler. The costs were also split into fixed and variable costs. Fixed costs (units in R/annum) included maintenance, salaries and wages, and depreciation. Depreciation was calculated as 20% of building costs. Variable costs (units in R/annum, R/week and R/bird) included electricity, water, cleaning of abattoir, packaging, distribution of live and end product, the cost to produce a whole, portioned and deboned bird ready for sale and the cost of a live broiler. In order to convert the per bird cost to a weekly cost of producing a whole, portioned and deboned bird ready for sale, the per bird cost was multiplied by the number of broilers sold per week (after mortalities) and then multiplied by the percentage of birds sold whole, portioned or deboned. The cost of a live broiler was determined by multiplying cost of a live broiler per kilogram by the final body weight of the live broiler. In order to convert this figure to a weekly cost, it was multiplied by the number of live birds entering the abattoir per week.

Total fixed and variable costs were calculated as the sum of all fixed and all variable costs in the units R/week and R/bird. In order to convert the units in fixed costs from R/annum to R/week, the sum of all fixed costs was divided by 52 weeks. In order to calculate the total fixed and variable costs in the units R/bird, the total fixed and variable costs in R/week were divided by the number of live birds entering the abattoir per week.

The total fixed and variable costs in R/week and R/bird were summed to give a total cost per week and cost per bird received. Mortalities were not considered significant as the numbers are usually low and the money spent on each bird was comparatively less as there are no feed costs involved.

Records of the birds and general information regarding the processing of the birds were entered under the production records heading. These included whole bird, portioned bird and deboned bird dressing percentage and the percentage of birds sold whole, portioned or deboned. The dressed bird as portions was then calculated as the percentage portioned bird dressing percentage of the whole bird dressing percentage. The dressed bird as deboned breast was calculated as the percentage deboned bird dressing percentage of the whole bird

dressing percentage. Other records included the percentage of contaminated carcasses, mortalities, or dead on arrivals, and the percentage of carcasses having scratches, bruises and damaged wings. From these records the total number of broilers sold per week was calculated, as well as the number of downgrades and A-grade broilers sold per week. The remaining 25% of the whole and portioned bird does not go to waste, especially in South Africa, where some of the remaining parts are considered delicacies. The weight of the feet, heart, gizzard and liver were recorded under production records for use in further calculations.

A source of income for a non-integrated processing plant would be a fee paid to the abattoir by the broiler farm. The main source of income for a processing plant is the sale of whole, portioned, deboned and downgraded birds as well as the feet, heart, gizzard and liver. The income per bird for a whole bird was calculated by multiplying the income per kg for a whole bird by the final body weight of the broiler and the whole bird dressing percentage. The income per week for a whole bird was calculated by multiplying the number of A-grade broilers sold per week by the percentage of the birds sold as whole birds and the income per bird for whole birds. The same calculations were used to determine the income per bird and per week for a portioned broiler, just replacing figures relating to whole birds with those from the portioned birds.

The calculation to determine income per bird for a deboned broiler is far more complex as only 20% of the dressed bird is sold as deboned breast, and the remaining 80% of the dressed bird is sold as portions. Therefore, the income per bird and per week was split into income derived from breast meat, and from the portioned broiler excluding the breast meat. In order to calculate the income per bird for breast meat, the percentage breast meat in the final dressed carcass must be established. This was determined by multiplying the dressed bird as deboned breast percentage by the whole bird dressing percentage. This value was then multiplied by the income per kg for breast meat, and the final body weight of the broiler, giving the income per bird for breast meat. Similarly, the percentage of portions, excluding breast meat, in the final dressed carcass must be determined in order to calculate income per bird for a portioned broiler excluding breast meat. This was determined by subtracting the dressed bird as deboned breast percentage from 100%, representing the percentage of the remaining portions, and multiplying this figure by the whole bird dressing percentage. This value was then multiplied by the final body weight of the broilers and income per kg for

portions. The income per week for both breast meat and the portions remaining after removal of the breast meat was calculated by multiplying the number of A-grade broilers sold per week by the income per bird for each respective part, and the percentage of birds further processed and sold as deboned breast.

Parts such as the feet, heart, gizzard and liver contribute a significant portion to the profit made by the processing plant, consequently their contribution to income per bird and per week was determined. The income per bird was simply calculated as the weight of the relevant part multiplied by income per kg for that part. The income per week was determined by multiplying the income per bird for the part by the total number of broilers sold per week. The final source of income for the processing plant is downgrades and was calculated as income per bird and per week. For reasons discussed in Chapter 1 under the processing section, damaged carcasses do not undergo further processing and are sold as whole birds. The income per bird was determined by multiplying the income per kg for downgrades by the final body weight of the broilers and the dressing percentage of the whole bird. The income per week was a simple multiplication of the number of downgrades sold per week by the income per bird for downgrades.

The total income per week was the sum of all income calculated per week, and the income per bird was calculated as the total income per week divided by the total number of broilers sold per week. The total profit was calculated per week, per bird and per kg. The weekly profit was calculated as a simple subtraction of the weekly costs from the weekly income. Similarly, the profit per bird was determined by subtracting the cost per bird received from the income per bird. The profit per kg is the division of the profit per bird by the final body weight of the broiler.

3.1.1.6 Economic Values

Egg production of the breeder hens
The value of this trait is obvious since increased egg production results in a greater number of broiler chicks. This improvement can manifest in one of two ways, fewer breeder hens would be required in order to produce a target number of broiler chicks, thereby reducing chick costs, or an increased number of broilers will be produced, spreading hen costs over

more offspring and translating into a greater profit being achieved. For the calculation of both EV's, an additional chick per hen was represented for the improvement of egg production.

The method of determining the cost EV involved calculating the difference in cost per hatching egg if each hen produced an extra chick (calculations performed in the Breeder Farm-Laying sheet). Firstly, the total number of hatching chicks was calculated, given the total number of eggs laid per hen and values for settable eggs, fertility and hatchability. The cost per hatching egg was then calculated by dividing the cost of housing that bird for 41 weeks (subtracting the income from eggs and meat for consumption and litter) by the number of hatching chicks. The cost per hatching egg was then determined if the hen were to lay an additional egg. The difference in cost represented the EV of an additional chick per hen.

The method of determining the revenue EV involved addition of the income per settable egg and the saving in cost of an additional chick per hen as calculated above.

AFE of the breeder hens
The aim of improving this trait is not to increase it, but decrease it, thereby bringing the birds into lay earlier, consequently the breeder hens are able to produce more eggs in the lengthened production cycle. The advantages of increased egg production were discussed above. Selection for AFE must be carefully managed and improvements exceeding a certain level should be avoided as it may have a negative influence on subsequent egg production. The egg weight for the production cycle may also be affected; the hen will produce a larger number of small eggs. Wilson (1991) has shown that small eggs can negatively affect the hatchability and final weight of broilers.

The cost EV for AFE was determined by calculating the effect of bringing the birds into lay a day earlier on the cost to rear the hen to sexual maturity (calculations performed in the Breeder Farm - Rearing sheet). This was determined by the basic costs incurred by each bird for each day it is present in the rearing house. This was calculated by dividing the sum of feed, electricity, water and fixed costs by the number of days the birds are in the rearing period. This cost per bird per day would be saved by the farmer if the birds were to reach sexual maturity a day earlier. Costs such as vaccination, purchasing of the breeders, shavings, gas and cleaning of the house were not included as they are incurred regardless of the period the birds remain in the rearing house.

The revenue EV for AFE also involved calculating the value of bringing the birds into lay a day earlier. Research performed by Lewis *et al.* (2008) investigating the relationship between illuminance and rate of sexual maturation and cumulative egg numbers, suggested a figure of 0.922 for loss in production per day delay in sexual maturity. This value was then multiplied by the income per settable egg and added to the saving in cost of bringing the birds into lay a day earlier as calculated above.

Fertility of the breeder hens

Increased egg production of a breeder hen would prove useless if the breeder hen possessed a poor fertility, as very few of her eggs would be fertile. Hence the importance of this trait, since it is directly related to the benefits of increased egg production. The cost EV of fertility was determined by calculating the effect an extra percent fertility would have on the cost to produce a hatching egg (calculations performed in the Breeder Farm-Laying sheet). Given the total number of settable eggs per hen, the number of fertile eggs per hen was calculated with an extra percent fertility. The total number of hatching chicks was then calculated from the hatchability value. The cost per hatching egg was then calculated by dividing the cost of housing that bird for 41 weeks (subtracting the income from eggs and meat for consumption and litter) by the number of hatching chicks with the extra percent fertility. The difference between the original cost per hatching egg, and the new cost per hatching egg with the extra percent fertility represented the saving in cost of an extra percent fertility.

The method of determining the revenue EV of an extra percent fertility involved subtracting the cost per settable egg from the income per A-grade chick sold and adding the saving in cost as calculated above. The cost per settable egg was subtracted from the income per A-grade chick sold, as this is the profit achieved by the hatchery if the egg sold to them is fertile.

Hatchability of the breeder hens

Increased egg production, or fertility, of a breeder hen would prove useless if the breeder hen possessed a poor hatchability, as the fertile eggs would not produce live broiler chicks. Consequently, hatchability is a valuable trait bearing the same significance and benefits as egg production. The cost EV of hatchability was determined by calculating the effect an extra percent hatchability would have on the cost to produce a hatching egg (calculations performed in the Breeder Farm-Laying sheet). Given the total number of settable and fertile eggs per hen, the total number of hatching chicks was calculated with an extra percent

hatchability. The cost per hatching egg was then calculated by dividing the cost of housing that bird for 41 weeks (subtracting the income from eggs and meat for consumption and litter) by the number of hatching chicks with the extra percent hatchability. The difference between the original cost per hatching egg, and the new cost per hatching egg with the extra percent hatchability represented the saving in cost of an extra percent hatchability.

The method of determining the revenue EV of an extra percent hatchability involved subtracting the cost per settable egg from the income per A-grade chick sold and adding the saving in cost as calculated above. The cost per settable egg was subtracted from the income per A-grade chick sold, as this is the profit achieved by the hatchery if the egg hatches.

Mortality

In an integrated operation, parent stock mortality is of significantly less economic importance than in their progeny, since the loss due to parent mortality is divided by the number of offspring per dam or sire (Pasternak *et al.*, 1986; Shalev & Pasternak, 1983), therefore mortality of the broilers was only considered. General costs of an operation are calculated exclusive and inclusive of mortality illustrating the importance of this trait. The motive behind this separation of costs is due to the significant cost of mortality at the end of each cycle. The principal influencing factor resulting in the significant cost of mortality are the feed costs, since feed costs comprise the majority of costs incurred by an operation. Therefore, a reduction in mortality represents less wastage of feed, a reduction in fixed and variable costs per bird, as well as a larger number of broilers for marketing. Therefore the interest in improving this trait should be considerable.

The cost EV of mortality was determined by calculating the saving in cost of a one bird reduction in mortality. This was calculated by summing the cost to purchase a day-old broiler, the vaccination cost per bird and half of the total feed costs per bird. It was assumed that the majority of these fatalities occurred midway through the production period, so the birds would only have consumed half the amount of feed required for the full production period. If not, they would have occurred at the beginning and at the end of the production period levelling to half the required feed intake. The above are significant costs incurred by each broiler raised on the farm. Therefore, if a broiler dies these costs remain with no benefit

to the operation. Thus, the above costs will be saved per bird with each reduction in mortality.

The revenue EV calculated the value of a one bird reduction in mortality. This value represented the opportunity cost of a one bird reduction in mortality. Thus, the saving in cost explained above was added to the selling price per bird at the end of the production period; since the farmer will fail to benefit from the sale of a bird if it has died.

Body weight of broilers

Since the aim of the broiler industry is to sell meat, improvement in this trait will directly influence the final profit achieved. An improvement in body weight would influence production in three ways, fewer broilers would be required in order to reach a certain target for number of kilograms produced per cycle, more broiler meat would be produced if the target number of broilers marketed remained constant, or time taken to reach target weight would be reduced, thereby reducing the costs incurred by that operation. For these reasons body weight is at the heart of all selection procedures.

The cost and revenue EV for body weight was determined by dividing the basic costs of raising each broiler by the number of days required to reach target weight (calculations performed in the Broiler Farm sheet). The basic costs included fixed, feed, electricity and water costs and represented the costs that could be saved should the bird reach target weight earlier than expected. The revenue EV did not include a further income as body weight was attained a day earlier and the target body weight achieved was fixed, thus no extra revenue was generated and the EV was the same as that for the cost.

FCR of broilers

Many of the positive outcomes of the traits discussed above were related to reducing feed costs, the most significant cost incurred by an operation. Therefore, motive for enhanced FCR needs very little introduction since it involves improved utilisation of feed which would save the industry a large amount of money if achieved. FCR is expressed as the ratio of total feed consumed to the final body weight. An improvement in FCR can occur due to an increase in body weight on the same amount of feed, or maintaining a certain body weight on less feed. The latter case is examined in this study. Target weight is reached a day early, hence, feed intake is reduced by a day. Therefore, the cost and revenue EV of FCR is

represented by the cost of a day's feed, calculated by dividing total feed costs per bird by the number of days taken to reach target weight (calculations performed in the Broiler Farm sheet). No income is associated with the revenue EV since FCR is not related to additional income, but rather a saving in cost, hence the cost and revenue EV's are identical.

Egg weight of the breeders

Egg weight does not normally hold a large weighting in a selection procedure as it is selected for indirectly due to the positive correlation it holds with body weight. A large weighting on egg weight would prove disadvantageous as large eggs will negatively affect hatchability (Wilson, 1991). Intermediate eggs are preferred, but the weight should be maintained at an upper level due to the strong positive correlation between egg weight and chick weight reported by Noy & Sklan (1997) and Wilson (1991). Furthermore, a 1 g change in egg weight has been shown to influence broiler body weight at six to eight weeks of age by 2-13 g (Wilson, 1991). Egg weights should, however, not exceed 70 g for the following reasons; the setters in the incubator do not hold eggs above this size, the setters will not cope with excessive egg weights and the constant egg shell quantity per egg will become limited with larger eggs causing the shell to become too thin (G. Griffin, 2009, Pers. Comm.[5]). Additionally, it is undesirable to have eggs below 50 g due to their influence on chick weight, and the setter size being unsuitable for this egg weight due to the increased risk of them falling out.

Egg weight is also correlated with egg production and AFE. If selection is applied to egg production, egg weight will decrease due to the reduction in AFE. Therefore, from a genetic standpoint smaller eggs are desirable, however, phenotypically the aim would be to have larger eggs. A solution when selecting for AFE would be to begin with stock possessing a higher egg weight which would prevent egg weight from dropping below the acceptable limit during selection. The cost EV of egg weight was determined by calculating the cost of a gram of egg weight (calculations performed in the Breeder Farm-Laying sheet). If egg weight were improved by a gram, this calculated cost would be saved by the farmer. This was determined by calculating the amount of feed required per egg; the feed intake per day was multiplied by the amount of days per egg laid. The amount of feed required per gram of egg weight was then calculated by dividing the amount of feed required per egg by the egg

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[5] G. Griffin, Gravic Farm Trust, P.O. Box 111, Dargle, 3265

weight. The cost of an extra gram of egg weight was then determined by multiplying the cost of feed per gram by the amount of feed required per gram of egg weight.

The revenue EV calculated the value of an extra gram of egg weight. Wilson (1991) found that 1 g of egg weight is synonymous with approximately 8 g of broiler body weight, therefore, the selling price per gram of broiler meat was calculated and multiplied by eight in order to calculate the benefit of an extra gram of egg weight. The saving in cost of an extra gram of egg weight, explained above, was then added to the revenue to represent the value of an extra gram of egg weight.

3.1.1.7 Sensitivity Analysis

The effect of production levels and product and feed prices on the EV's generated by the model was determined. The EV's representing the additional value created by the improvement were chosen since they reflected the benefit to the revenue as well as the saving in cost. Varying production levels were applied only to egg production and body weight, being the traits of importance to the study. Egg production levels were calculated as an additional 10 hatching chicks per hen and a loss of 10 hatching chicks per hen compared to the basal value.

In this exercise interest was in increasing and decreasing the target body weight of the birds. The body weight levels were calculated as an additional 1 kg on the target weight, and a reduction of 1 kg to the target body weight. Since the time taken to reach target weight would remain constant, or increase with the increasing body weight, there was no saving in cost as the bird was still present for that period and still consumed the specified amount of feed. Therefore, the improvement, or reduction, in body weight was represented by an increase, or decrease, in the revenue achieved.

The settable egg price was doubled and halved and the selling price per kg was doubled and halved. Since the original EV calculation of revenue for body weight did not include the benefit of an increase in revenue, the body weight EV calculation was amended and calculated as the difference in selling price per bird when the price was adjusted. Total feed costs at the rearing, laying and broiler farm were doubled and halved to determine their effect on the revenue EV's of the economically important traits.

Eight different levels of egg production, body weight, egg price and body weight price were plotted against their relative EV to determine the relationship between the levels and the EV. Changes in the egg production EV were determined when egg production varied from 227 to 28 hatching chicks and egg price from R 3,50 to 44 c per settable egg. Changes to the body weight EV were recorded between a body weight of 3,96 to 0,50 kg and the pricing from R14,30 to R 1,79 per kg. Eight levels of feed price, starting at R 95,13 to R 11,89 per bird, were also plotted against the egg production and body weight EV to determine their relationship.

3.1.2 Results

The values in the table below resulted from the economic evaluation that was performed in 2008.

Table 3.1   The economic values of traits of economic importance calculated as a saving in cost and as additional revenue

	Cost-EV	Revenue-EV
Additional chick per hen	R 0,02	R 1,77
Entering lay a day early	R 0,25	R 1,87
Extra percent fertility	R 0,02	R 0,97
Extra percent hatchability	R 0,02	R 0,97
1 bird reduction in mortality	R 7,63	R 21,78
Reaching target body wt 1 day early	R 0,24	R 0,24
Reducing FCR by a days feed intake	R 0,22	R 0,22
Extra gram of egg weight	R 0,01	R 0,07

3.1.2.1 Sensitivity analysis

The table below illustrates the effect of production levels and product and feed prices on the EV's generated by the model constructed in this study.

Table 3.2   The production level and product price adjustments made to egg production and body weight, and their influence on the remaining economically important traits, as well as the effect of feed price fluctuations on the economically important traits

	Egg Prodn	AFE	Fertility	Hatch-ability	Mortality	Body Wt	FCR	Egg Wt
Egg Prod level inc.	R 17,65	R 1,87	R 0,97	R 0,97	R 21,78	R 0,24	R 0,22	R 0,07
Egg Prod level dec.	-R17,68	R 1,87	R 0,97	R 0,97	R 21,78	R 0,24	R 0,22	R 0,07
Body Wt level inc.	R 1,77	R 1,87	R 0,97	R 0,97	R 28,93	R 7,15	R 0,22	R 0,07
Body Wt level dec.	R 1,77	R 1,87	R 0,97	R 0,97	R 14,63	-R 7,15	R 0,22	R 0,07
Egg Price inc.	R 3,52	R 3,48	-R 0,78	-R 0,78	R 21,78	R 0,24	R 0,22	R 0,07
Egg Price dec.	R 0,90	R 1,07	R 1,84	R 1,84	R 21,78	R 0,24	R 0,22	R 0,07
Body Wt Price inc.	R 1,77	R 1,87	R 0,97	R 0,97	R 35,94	R 14,16	R 0,22	R 0,13
Body Wt Price dec.	R 1,77	R 1,87	R 0,97	R 0,97	R 14,71	-R 7,08	R 0,22	R 0,04
Feed Price dec.	R 1,76	R 1,80	R 0,96	R 0,96	R 19,57	R 0,13	R 0,11	R 0,07
Feed Price inc.	R 1,78	R 2,01	R 0,99	R 0,98	R 26,21	R 0,46	R 0,44	R 0,07

The shaded cells are traits unaffected by the changes made to either a production level or product price of egg production and body weight, or the feed price changes. Changes to product and feed prices had a larger effect on the EV's than changes made to the production levels of egg production and body weight. Feed prices had the largest impact on the EV's of the traits.

Upon plotting the varied production levels and product prices of egg production and body weight with their EV's, it became clear that these resulted in linear relationships in all cases. Furthermore, feed price also exhibited a linear relationship with body weight and egg production EV's.

3.1.3 Discussion

The model was used to determine the EV's for eight chosen traits based on the information supplied by various farmers. The resulting EV's are representative of a specific set of circumstances. Since the data was obtained from various farmers in KwaZulu-Natal in 2008, it is specific to their situation and might not be applicable to other poultry farmers in South Africa. However, it reveals valuable information to the concerned farmers. The EV's were calculated under differing criteria as a saving in cost per incremental improvement in the trait of interest and an increase in value per incremental improvement in the trait of interest.

The method of calculation and the units of improvement must be considered when comparing the EV's. The cost EV's provide a better measure of comparison since they include only a saving in cost calculation for each trait. When calculating the revenue EV's some traits have a saving in cost and revenue associated with them, whilst others consider only a saving in cost. Therefore, when comparing the cost EV's, the noteworthy traits are AFE, mortality, body weight and FCR. A sensitivity analysis was also run to determine the sensitivity of the EV's to various changes in the inputs. The noteworthy findings of the model will be discussed.

It was unexpected for AFE to have a greater EV than egg production, given the economic importance of egg production, however, the reason for this is the method of EV calculation. A reduction in AFE of one day implies that the birds can leave rearing a day early, reducing the basic daily costs incurred to the rearing farm by one day. An additional chick per hen does represent a saving in cost, but since the saving in cost is divided by the total number of hatching chicks, it does minimise the value. Similarly to the study performed by Jiang *et al.* (1998), fertility and hatchability share the same EV's since they are both contributing to an increased number of day-old chicks.

Naturally mortality would display a large EV since it represents a considerable loss to the farmer as all significant costs incurred by the bird are deemed losses since they add no profit to the operation. The large EV of body weight and FCR illustrate their value to the broiler operation.

The model is not limited to generation of EV's. Of additional interest is the sensitivity of the EV's to changes in prices, the evolving requirements of the market and the changes that occur in the economically important traits of the broiler and breeder due to genetic selection. Improvement in egg production is represented by a saving per hatching egg and an increase in revenue owing to the extra eggs, since the laying period remains constant, and the birds lay more eggs. Conversely, if the number of hatching eggs is reduced, the cost per hatching egg will increase and revenue will decline. Altering egg production had no effect on the other traits of importance. Body weight influenced the mortality EV since the advantage of an improvement in body weight, or the disadvantage of a reduction in body weight, is lost due to the mortality of a bird.

A change in egg price affected AFE, fertility and hatchability. An increase in settable egg price would benefit AFE, as the earlier the hens come into lay, the more they are able to take advantage of the increase in price. Equally, a decrease in settable egg prices would reduce the importance of improvement to AFE. An increase in settable egg price, without a concurrent increase in price of A-grade chicks, would prove unfavourable to fertility and hatchability as the hatchery's profit margin would be reduced. However, a decrease in the settable egg price, without a concurrent decrease in the selling price of A-grade chicks, would prove advantageous and boost the profit margin of the hatchery. Body weight prices again influenced the mortality EV for the same reasons explained above, however, it also affected the egg weight EV. Since an improvement in egg weight has proven to positively influence broiler body weight, the value of improving egg weight is amplified with an increase in broiler body weight prices. Conversely, a reduction in broiler body weight prices removes the added value of improving egg weight.

The impact of feed price fluctuations on the egg production EV was negligible. The reason for this is that the total cost per bird is divided by the total number of hatching chicks per hen, thus the increase or decrease in feed price is minimised by this division. The same concept applies to fertility and hatchability, since costs are divided by the total number of hatching chicks due to an increase in fertility or hatchability. The fluctuating feed prices had a larger effect on AFE since feed costs constituted the largest saving in cost with a reduction in the rearing period.

The fluctuating feed prices would have a definite impact on the mortality EV, since feed costs represent a portion of the loss to the farmer. Increasing feed costs would add significantly to the losses made by the farmer since the bird consumes feed, but dies and does not contribute towards the profit. The farmer would still incur a loss when the feed costs are reduced, however this loss would be minimised. The feed price also affected the body weight EV which was calculated as the saving in cost of reaching target body weight a day earlier. Achieving target weight a day early is not as valuable with lowered feed costs since the cost of production per bird has been lowered. If the feed costs are increased, the value of reaching target weight a day early is amplified due to the larger production cost. The doubling and halving of the feed costs simultaneously doubled and halved the FCR EV. It is obvious that the value of superior FCR would increase with increasing feed costs, and decline with a decrease in feed costs.

The egg weight EV was not affected by the changing feed costs. The EV was calculated as the value of an extra gram of egg weight, which would represent the cost of feed to deposit a gram of egg weight. Although the feed prices were changed, they become insignificant when broken down to a gram of egg weight. An error by the model is that market changes that would occur with a change in feed price are not taken into account. Feed price, being the dominant production cost of an operation, controls the market price of the main products. Had this been taken into account, further changes to each of the EV's would have occurred due to their adjusted selling price. A change in the egg weight EV also would have occurred since the broiler selling price would have changed.

The principles discussed from the literature apply to the model constructed in this study. An increase in feed costs increases the value of any trait as the importance of improving the productivity of the animal is imperative due to the high cost of production.

Jiang *et al.* (1998) also investigated the sensitivity of the EV's to production levels and product and feed prices. The authors found the relationship between the EV's and the production circumstances to be both linear and nonlinear. An increase in a product price leads to a linear increase in the EV of the trait directly influencing the output of the corresponding product, while changes to the production levels of traits exhibit a nonlinear relationship with the EV's. In this study all relationships proved linear. This result was expected as an increase in the product price will lead to a proportional increase in the EV as

the product can now achieve a greater profit for the farmer. Furthermore, an increase in the production level would result in a linear increase in the EV since the bird would earn proportionately more income for the farmer. The difference between this study and that performed by Jiang *et al.* (1998) could be the method of calculation of the EV's.

3.2 Index Selection

The need for multiple trait selection is evident from the results of the negative impact of single trait selection on the correlated traits of selection. Previous studies have compared the performance of single trait with index selection. Osborne (1957) and Kinney *et al.* (1970) found sire family selection to produce better results than index selection. The poor performance of index selection is surprising, however, it is known for its ability to simultaneously improve multiple traits. The improvement of only one trait was the focus of the study, therefore the full benefit of index selection was not exercised. Yamada (1958), however, found index selection to achieve maximum progress over single trait selection, particularly in the presence of unfavourable genetic correlations existing between the traits under selection.

It will be determined whether index selection is capable of improving all four traits simultaneously, and whether it can match the improvements that were made to the traits in any of the four single trait selection procedures used. Furthermore, it will be established whether index selection is in fact the most effective selection procedure.

3.2.1 Materials and Methods

The Excel spreadsheet that was designed for single trait selection was modified for use in index selection. Since index selection is applied to individuals, and not families, the template for individual selection (IS) was used. It is the calculation of an index value that distinguishes index selection from the single trait selection strategies. The index value represents the genetic economic value (GEV) of the individual as a whole, taking into consideration all traits of economic importance. Calculation of a GEV for each trait, or b-value, is required for the index value. The methodology used for the selection index will be described below.

3.2.1.1 Calculation of b-values

Calculation of the index value for index selection requires genetic parameters and EV's. These values are multiplied together, producing the b-values or GEV's. Since more than one trait is selected for, a phenotypic and genotypic matrix must be constructed, and their

phenotypic and genetic correlations must be represented to illustrate the relationship between these traits.

The phenotypic matrix was constructed first. Since four traits were selected for, the matrix was made up of four rows and four columns. The first column in the first row represented the phenotypic variance of the first trait (J. De Guisti, 2008, Pers. Comm.[6]); this was calculated by squaring the standard deviation (SD) of the first trait (Falconer & Mackay, 1996). The following three cells on the diagonal also calculated the phenotypic variance of the remaining three traits. The remaining three columns of the first row were used to calculate the phenotypic covariance between the first trait and the remaining three traits in turn. This was obtained by multiplying the phenotypic correlation between the first trait, and each of the remaining three traits, by the SD of each trait considered in the multiplication. The remaining three rows in the first column were used to mirror the phenotypic covariance calculation. The remaining two columns in the second row were used to calculate the phenotypic covariance between trait number two and the remaining two traits. The fourth column in the third row was used to calculate the phenotypic covariance between trait number three and the remaining trait. The phenotypic covariance was now calculated for each combination of the four traits. The third and fourth row of the second column, and the fourth row of the third column, was used to mirror the phenotypic covariance of the second and third trait with the remaining traits. This completed the phenotypic matrix.

Calculation of the b-values required an inversion of the phenotypic matrix. The "Minverse" function was used in Excel to invert the phenotypic matrix as described above (J. De Guisti, 2008, Pers. Comm.[6]).

The genotypic matrix was calculated similarly to the phenotypic matrix, apart from the use of genetic rather than phenotypic values in the calculations. The genetic variance was calculated by multiplying the heritability, of the concerned trait, to the phenotypic variance, of the concerned trait. The genetic covariance was calculated by multiplying the genetic correlation between the two traits to the genetic SD of each trait. The genetic SD of the concerned trait was the square root of the genetic variance of the concerned trait. The genotypic matrix was then calculated with the four rows and columns set up similarly to the phenotypic matrix.

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[6] J. De Guisti, jon.deguisti@gmail.com

The EV's for each trait were entered into a table and comprised the a-matrix. The "genetic" information for each of the the four traits was then calculated by multiplying the inverse of the phenotypic matrix to the genotypic matrix. The function "Mmult" was used in Excel to perform this task. The economic and "genetic" values were then merged to determine the b-values, again using the "Mmult" function (J. De Guisti, 2008, Pers. Comm.[6]). It must be noted that a negative sign was placed in front of the AFE b-value. If the b-value was assigned a large positive value this would signify that the improvement of AFE is of importance to the selection index. Therefore, changing to a negative sign will assist in the improvement of that trait since the aim is always to reduce this trait. Where the AFE b-value was already negative, it was not made positive.

3.2.1.2 Selection methodology

The IS template was modified for use in index selection. A column was set aside, adjacent to the population values, for the calculation of the index values using the formula of Falconer (1981):

$$I = b_1 P_1 + b_2 P_2 + b_3 P_3 + ...$$

The "b" in the equation represents the b-values which were calculated using the methods explained above. The "P" represents the phenotypic value for that particular trait. An index value was calculated for each individual, and in this study focuses on four traits for each individual.

The starting means of each of the traits were entered above the population. Random numbers were generated until the mean and SD of the population loosely corresponded with the mean and initial SD that was entered. The population mean and SD were then copied and the values were pasted into the "Results" worksheets. Figure 3.1 below illustrates the worksheet containing the parent population, as well as the index values.
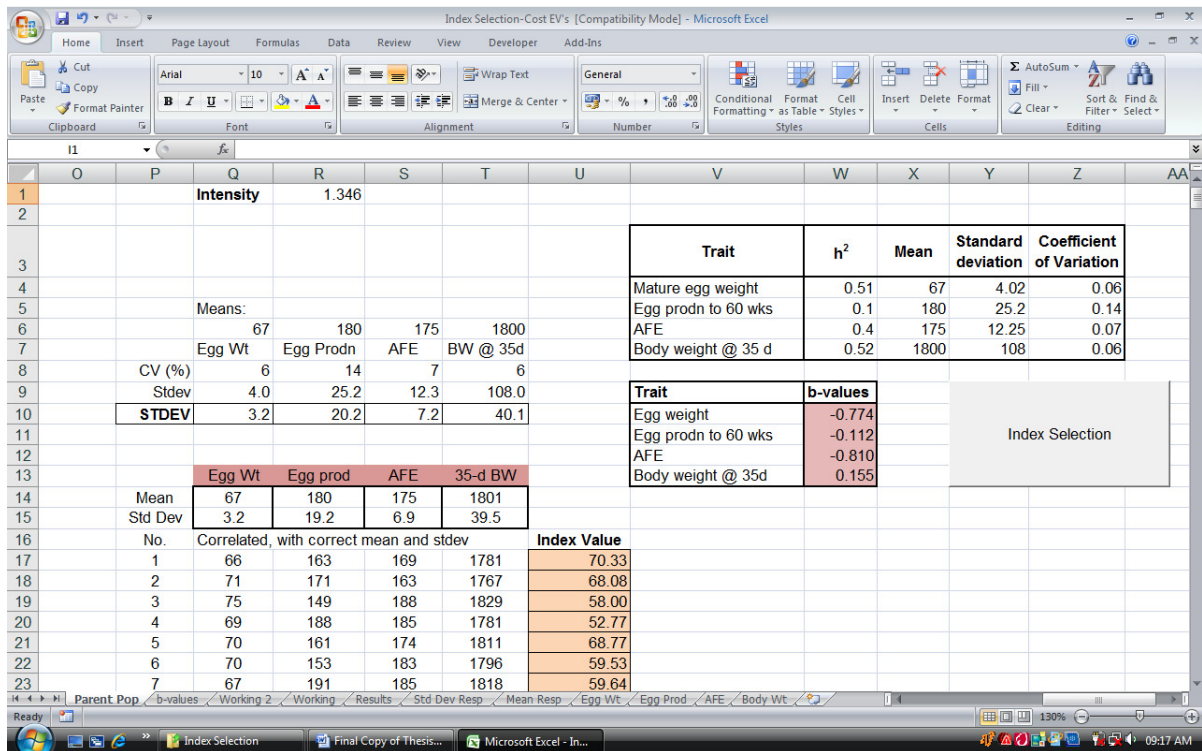
Figure 3.1 The Microsoft Excel file for Index Selection showing part of the parent population with the starting values, standard deviation, b-values and index values

The macro began recording given the following instructions: each individual's phenotypic value for each trait, and their corresponding index value, was copied, and the values were pasted into the "Working 2" worksheet. It is important that the index values remain with the particular individual as selection will be based on the index values. All values, still highlighted in the "Working 2" worksheet, were then sorted in descending order according to the index values. It is imperative that all values are highlighted, and not just the index values, as the individual belonging to the particular index value must be moved to the appropriate position in the population.

The top 110 individuals (corresponding to an intensity of selection of 1.346) with the highest index values were highlighted and copied into the "Working" worksheet. The response to selection was calculated adjacent to the selected parents. Since each trait is selected for under index selection, it would seem correct to use the direct response to selection equation. However, use of the direct response equation allowed for unrealistic progress in each trait

simultaneously with disregard for the negative correlations that exist between some of the traits. Therefore, only the simulated method was used for index selection and the response was calculated by subtracting the mean value of the trait for the population, before selection, from the mean value of the trait for the selected parents, and multiplied by the heritability. This response to selection was added to the mean of the previous generation to determine the mean value of the offspring for the following generation.

Once these values were determined, they were pasted where the starting means were located from which the population was generated. The macro was then stopped and a button was inserted that would be pressed each time the macro was required to operate. The population would now be generated from the new means that were inserted. The formula that was used to generate the population using the initial SD was now changed to incorporate the average SD. This change was made for every individual and every trait.

Random numbers were then generated using the procedure described in Chapter 2, section 2.1, until the mean values for all traits of the population loosely corresponded with those that were pasted from the worksheet calculating the response to selection. Additionally, the SD of the population had to correspond with the new SD that was being used. These means and SD's were copied, and the values were pasted into the "Results" worksheet as explained above. The macro was then run and the process repeated itself until 10 generations of mean values were produced.

In order to determine the impact of the EV's on the performance of egg production and body weight, the revenue EV's were recalculated by the model for differing levels of egg production and body weight. The selection index was rerun, using each of the four new b-values in turn, for 10 generations. The selection index was also run incorporating the cost and revenue EV's to determine their response. Interest would lie in manipulating the EV's for egg production and body weight, to assign a large weight to both of these traits in a single index and determine whether they may improve simultaneously.

An attempt was made to simultaneously improve the values of body weight and egg production. It proved rather difficult to manipulate the b-values to the required level by adjusting the EV's, since the genetic values of the individual also play a role. Hence, the b-values were changed manually in an attempt to determine the capability of the selection index

to improve both egg production and body weight. It is important that the b-value of body weight was not made too large as this forces egg production to decline due to the negative correlation that exists between the two traits and the poor heritability of egg production, making it difficult to achieve any progress. Therefore, the egg weight and AFE b-values were assigned nil values, and body weight and egg production were assigned b-values of 2.0 and 10.0 respectively. This exercise would prove to be the ultimate test for the selection index.

A table was constructed to compare the overall value of all five selection strategies. Each strategy was assigned an index value, representing the overall worth of the population when selection was applied to a certain trait. The index value was calculated using the same formula as described above. The b-values, obtained from the cost EV's, were used in the index calculation, as well as the phenotypic values from each trait, taken as the mean of the population, using the simulated method, from generation five and 10. Selection for all four traits was examined, and in the case of index selection, procedures were chosen that maximised the potential of the selection index. The procedure achieving the greatest response in each of the four traits was not chosen for the index calculation, as in most cases the trait was given a significantly larger EV than the other three traits, and would be much the same as applying single trait selection.

3.2.2 Results

Graphs are used to illustrate the response to increases and decreases in the EV of egg production and body weight. Most importantly, the response to a simultaneous improvement in egg production and body weight will be revealed. The associated economic- and b-values are displayed alongside each of the graphs. Finally, the value of the population after five and 10 generations of selection with each of the five selection strategies, according to the cost EV's, are compared with the use of a table.

3.2.2.1 Increased target body weight

Figure 3.2 illustrates the impressive improvement that is made in body weight when this is given a large economic weighting (Table 3.3). The progress does not appear to slow, mainly due to conservation of the SD, which is 40.8 in generation 10, by which time the selection index has achieved a proportional increase in body weight of 1.15. Egg weight and egg production are not favourably affected by the index, losing 6 g and seven eggs. This may be due to the low EV of egg weight and the negative correlation between egg production and body weight. AFE does, however, benefit from the index and in generation 10 is reduced by 20 days. This may be due to the favourable EV, as well as the positive correlation between AFE and body weight, which is much stronger than that between egg weight and body weight, perhaps placing more emphasis on the improvement of AFE. The b-value for AFE was surprisingly high given that the EV for body weight was so much larger than that for AFE. A possible reason for this may be the relationship of AFE with egg production and body weight. By placing a large weighting on AFE it will aid in the reduction of egg production and improvement of body weight, being an aim of the selection index. However, the b-value was made negative to direct the improvement of AFE, possibly reducing the ability of the selection index to reduce egg production and improve body weight as much as is possible. Nevertheless, body weight does make a marked improvement.

Table 3.3 Economic- and b-values for egg weight, egg production, AFE and body weight associated with an increase of 1 kg to target body weight

	Egg Weight	Egg Prodn.	AFE	Body Weight
Economic Value	0.07	1.77	1.87	7.15
b-value	-23.809	-3.009	-21.393	4.428

Figure 3.2 Response in egg weight, egg production to 60 weeks, AFE and body weight at 35 days (secondary axis) following index selection for an increased target body weight (◆Egg Weight, ■Egg Production, ▲AFE and ●Body Weight)

3.2.2.2 Decreased target body weight

Figure 3.3 illustrates the vast reduction that is made in body weight when its EV is reduced (Table 3.4). Surprisingly, the selection index is not able to maintain the SD of body weight as efficiently as when positive selection is applied to body weight, reaching 19.3 in generation

10. The resulting value of body weight in generation 10 is 0.83 of the initial value of body weight. Unexpectedly, the b-value of egg weight was the largest of all traits although it had an insignificant EV and has a positive correlation with body weight. The resulting value for egg weight was not that intended by the selection index and lost 3 g in value by generation 10. This may be due to the negative movement of AFE and body weight, both having a positive relationship with egg weight, and the positive movement of egg production, having a negative relationship with egg weight. AFE and egg production, however, benefit from the index and in generation 10 AFE is 27 days earlier and egg production achieves an extra 10 eggs. AFE having the largest EV was assigned the most negative b-value in order to direct the trait towards a reduction to assist in the lowering of body weight, and perhaps the improvement in egg production. As expected the positive EV of egg production resulted in a positive b-value given the large negative correlation that exists between egg production and body weight.

Table 3.4 Economic- and b-values for egg weight, egg production, AFE and body weight associated with a loss of 1 kg to target body weight

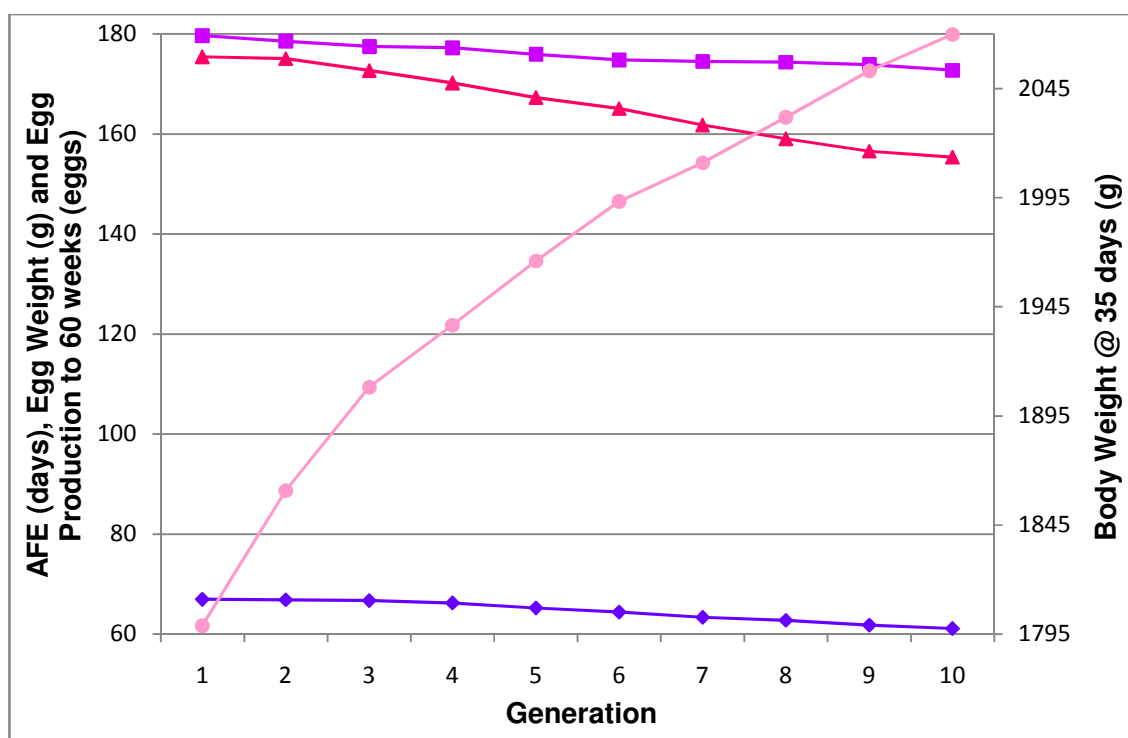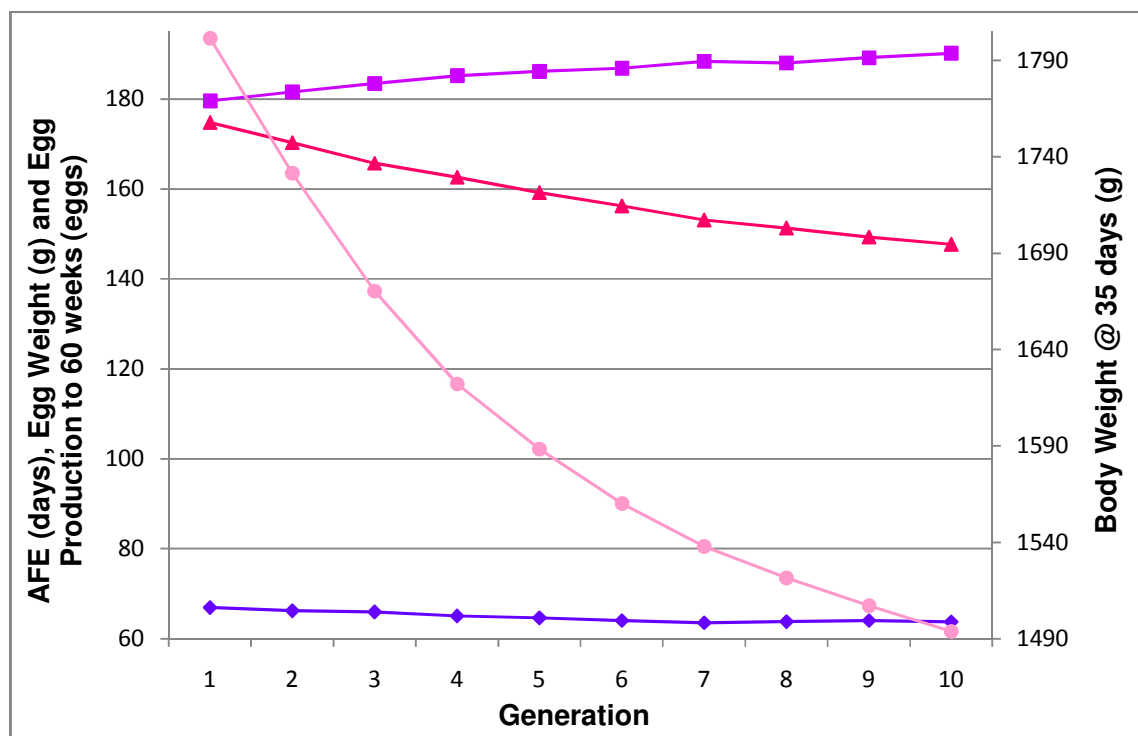|	Egg Weight	Egg Prodn.	AFE	Body Weight
Economic Value	0.07	1.77	1.87	-7.15
b-value	22.697	3.216	-20.382	-4.417

Figure 3.3   Response in egg weight, egg production to 60 weeks, AFE and body weight
at 35 days (secondary axis) following index selection for an decreased target
body weight (◆Egg Weight, ■Egg Production, ▲AFE and ●Body Weight)

3.2.2.3 Increased egg production

Figure 3.4 illustrates the positive effect of an increase in EV of egg production (Table 3.5) on
the performance of the trait.   The large weighting does, however, reduce the SD of egg
production in generation 10 to 5.0. This value, nevertheless, will allow for further progress to
be achieved. A proportional increase of 1.07 is achieved in egg production by generation 10.
Egg weight, AFE and body weight all receive negative b-values and experience a
corresponding decrease to their values. A large negative b-value resulted for egg weight
given its insignificant EV and negative relationship with egg production. The b-value for body
weight was not as largely negative as egg weight, given its larger EV, maintaining its
importance to the selection procedure. Despite the fact that AFE had a considerable EV, it
became insignificant as it was more the R15 under that of egg production. Therefore, the
importance of AFE to the index is in its relationship with egg production. By reducing AFE,
egg production levels will be increased due to the negative correlation that exists between the

two traits, hence the b-value of AFE was negative. Thus, the b-value was left negative to assist in the improvement of egg production. The values of egg weight and body weight were reduced by 11 and 313 g respectively, while AFE was reduced by 27 days.

Table 3.5 Economic- and b-values for egg weight, egg production, AFE and body weight associated with an additional ten hatching chicks

	Egg Weight	Egg Prodn.	AFE	Body Weight
Economic Value	0.07	17.65	1.87	0.24
b-value	-7.252	1.543	-1.850	-0.299

Figure 3.4 Response in egg weight, egg production to 60 weeks, AFE and body weight at 35 days (secondary axis) following index selection for an increased egg production (◆Egg Weight, ■Egg Production, ▲AFE and ●Body Weight)

3.2.2.4 Decreased egg production

Figure 3.5 illustrates the reduction made in egg production when its EV is reduced (Table 3.6). The resulting value in generation 10 is 0.94 of the initial value of egg production. Fortunately, egg weight, AFE and body weight are positively affected by the decrease in egg production and are all assigned positive b-values. Obviously the AFE b-value was converted to negative since the aim is to reduce the value of this trait. Thus, all traits experienced an improvement to their value. An improvement in egg weight and body weight does correspond to a decline in egg production, however, a reduction in AFE does not correspond to a reduction in egg production since more eggs are laid the earlier the hen comes into lay. Furthermore, a reduction in AFE is not normally associated with an improvement in egg weight and body weight. This is an example of index selection working against the negative correlation that exists between egg production and AFE, and the positive correlation that exists between AFE and egg weight and body weight. By generation 10, egg weight achieves an extra 6 g, AFE is 14 days earlier and body weight gains 288 g.

Table 3.6 Economic- and b-values for egg weight, egg production, AFE and body weight associated with a loss of ten hatching chicks

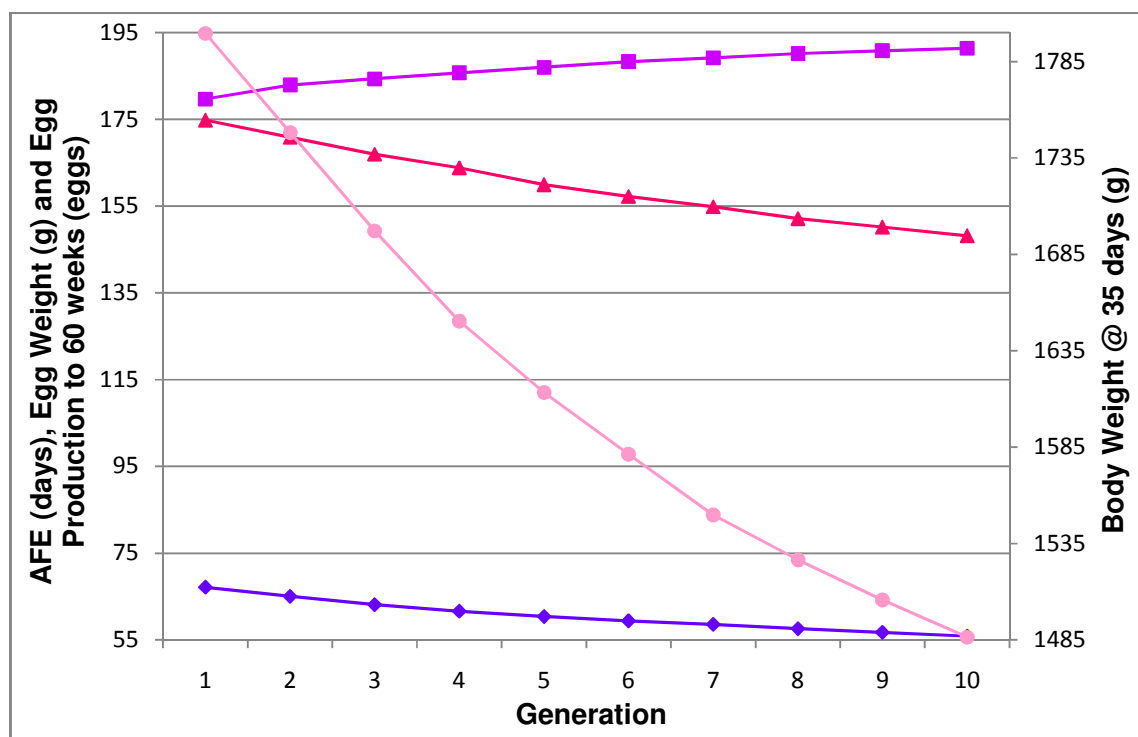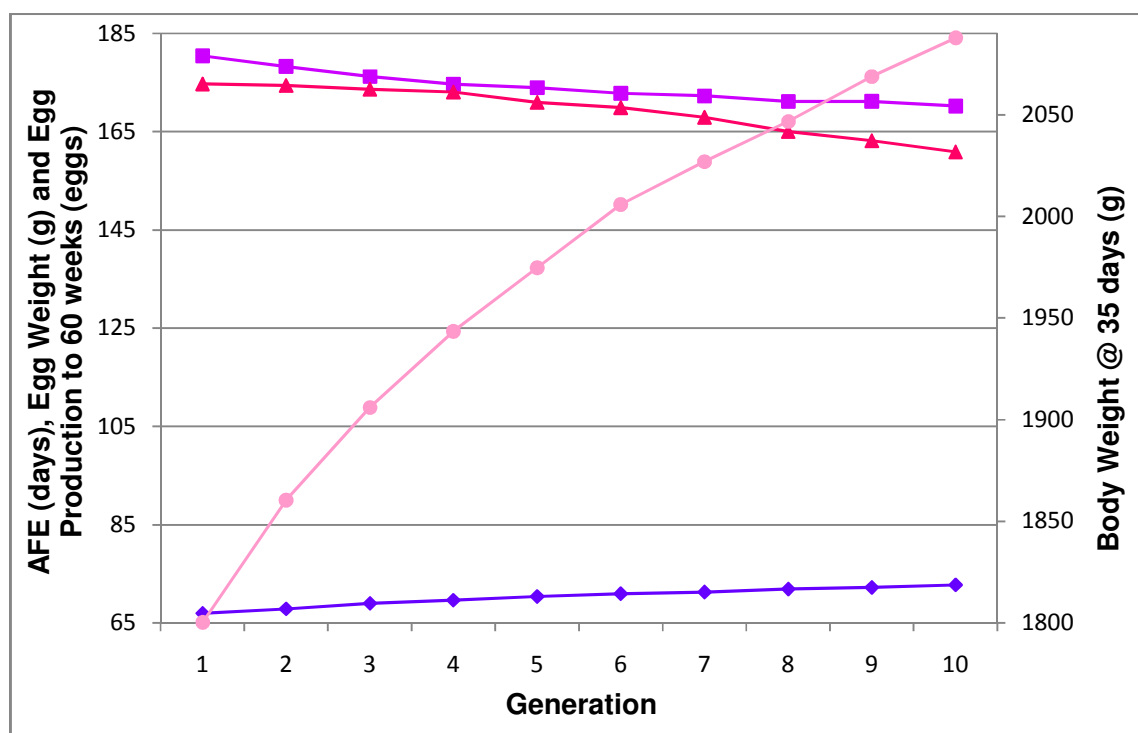|	Egg Weight	Egg Prodn.	AFE	Body Weight
Economic Value	0.07	-17.68	1.87	0.24
b-value	5.908	-1.892	-4.951	0.710

Figure 3.5 Response in egg weight, egg production to 60 weeks, AFE and body weight at 35 days (secondary axis) following index selection for an decreased egg production (◆Egg Weight, ■Egg Production, ▲AFE and ●Body Weight)

3.2.2.5 Revenue

Table 3.7 illustrates the emphasis that the selection index has placed on AFE given the revenue EV's. In generation 10 AFE achieves a value that is 0.88 of the initial value (20 day decrease). Various genetic factors have minimised the importance of egg production to the selection index, despite its large EV, making body weight the second most significant trait to the selection index. Body weight had a relatively lower EV than egg production and AFE, but given it's favourable heritability and relationship with AFE, having the highest EV, it's resulting b-value was higher than that of egg production causing it to achieve a proportional increase of 1.15 by generation 10 (263 g increase). Both AFE and body weight maintain a satisfactory SD in generation 10 of 5.2 and 53.2, respectively. Egg weight is reduced by 9 g while egg production remains fairly stationery and loses only one egg per year. The EV of egg production was close to zero despite it having the second highest EV. This is due to its poor

heritability and may also be due to its negative correlation with AFE which had the highest EV.

Table 3.7 Revenue economic value and associated b-values for egg weight, egg production, AFE and body weight

	Egg Weight	*Egg Prodn.*	*AFE*	*Body Weight*
Economic Value	0.07	1.77	1.87	0.24
b-value	-1.337	-0.001	-1.207	0.154

Figure 3.6 Response in egg weight, egg production to 60 weeks, AFE and body weight at 35 days (secondary axis) following application of the revenue EV's to the selection index (◆Egg Weight, ■Egg Production, ▲AFE and ●Body Weight)

3.2.2.6 Cost

Table 3.8 illustrates the emphasis that the selection index has once again placed on AFE given the cost EV's. Moreover, body weight is yet again the second most significant trait to the selection index. This result was expected since the EV's of AFE and body weight were more than 20c above that of egg weight and egg production. This illustrates the obvious EV of these two traits to the broiler industry. Consequently, in generation 10 AFE achieves a value that is 0.90 of the initial value (17 day decrease), while body weight achieves a proportional increase of 1.16 (292 g increase). The SD of both traits remains satisfactory in generation 10 with AFE at 7.5 and body weight at 41.7. Egg weight and egg production are again reduced; egg weight by 4 g and egg production by nine eggs.

Table 3.8   Cost economic value and associated b-values for egg weight, egg production, AFE and body weight

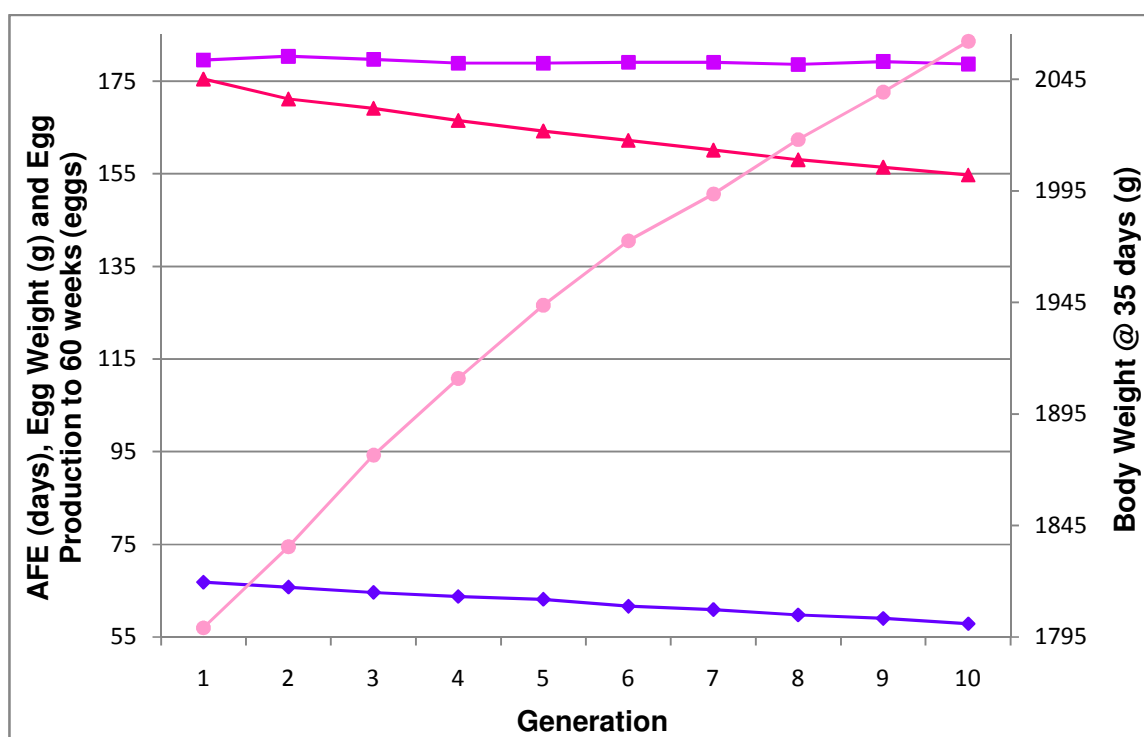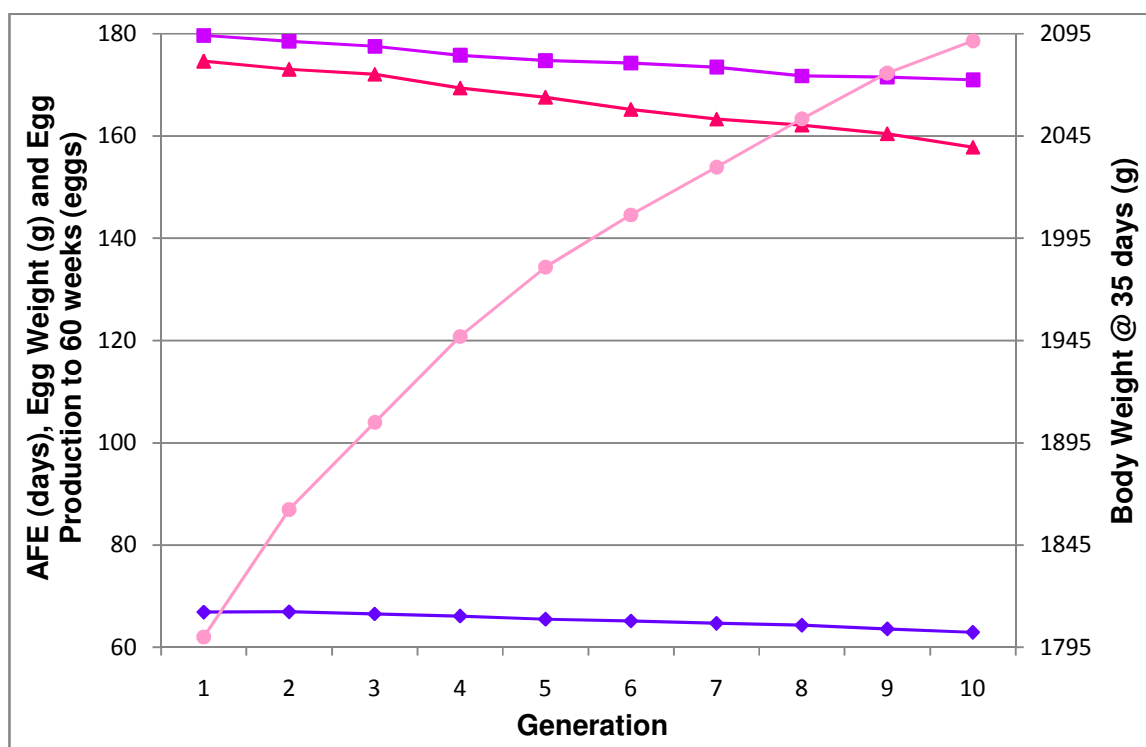|	*Egg Weight*	*Egg Prodn.*	*AFE*	*Body Weight*
Economic Value	0.01	0.02	0.25	0.24
b-value	-0.774	-0.112	-0.810	0.155

Figure 3.7   Response in egg weight, egg production to 60 weeks, AFE and body weight at 35 days (secondary axis) following application of the cost EV's to the selection index (◆Egg Weight, ■Egg Production, ▲AFE and ●Body Weight)

3.2.2.7 Simultaneous improvement in egg production and body weight

In order to put the selection index to the ultimate test each trait was assigned a b-value in an attempt to control their progress with the selection index. No improvement is desired in egg weight and AFE, hence they were assigned nil b-values, as the interest lies in the improvement of egg production and body weight, given b-values of 2.0 and 10.0, respectively (Table 3.9). These b-values were found to be most suitable to allow for adequate progress in both egg production and body weight. The EV's were not manipulated since assigning a nil value does not guarantee the relevant traits will be fixed, since genetic factors and the relationship of the trait with one of economic importance will influence the progress achieved in the trait. Egg weight and AFE nevertheless experience a slight change, a reduction of 5 g in egg weight and an additional two days to reach sexual maturity. The negative correlation between egg weight and egg production is stronger than the positive correlation between egg

weight and body weight, causing the slight decrease made in egg weight. The relationship between AFE and body weight and egg production is of the same strength, however, in differing directions. Thus, AFE was slightly more influenced by the movement of body weight.

Remarkably, both egg production and body weight experience an increase above their initial values. Body weight achieves a proportional increase of 1.14, translated to a 259 g increase by generation 10, and egg production achieves a proportional increase of 1.05 or an extra eight eggs by generation 10. Even further advantages exist, as the SD of body weight and egg production at generation 10 is 55.6 and 10.6 respectively, hence the possibility of improvements beyond generation 10.

Table 3.9   Economic- and b-values for egg weight, egg production, AFE and body weight associated with a simultaneous increase in the value of egg production and body weight

	Egg Weight	Egg Prodn.	AFE	Body Weight
Economic Value	0	0	0	0
b-value	0	10.00	0	2.00
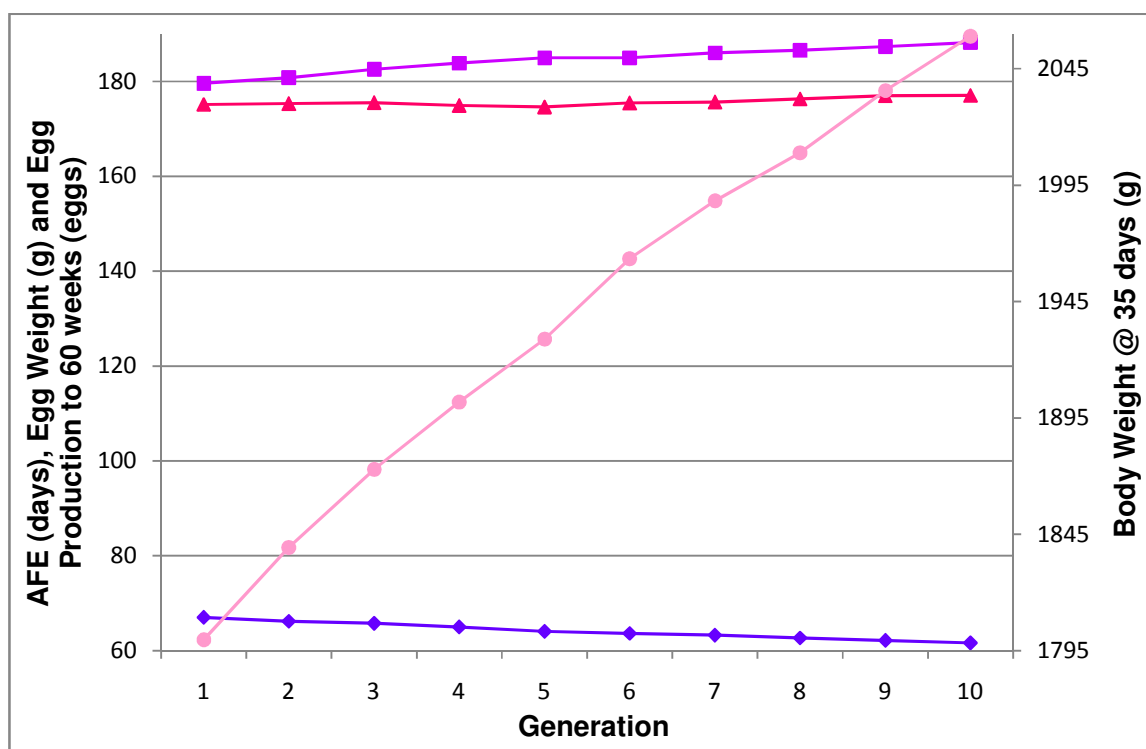
Figure 3.8 Response in egg weight, egg production to 60 weeks, AFE and body weight at 35 days (secondary axis) following index selection for an increased egg production and body weight (◆Egg Weight, ■Egg Production, ▲AFE and ●Body Weight)

3.2.2.8 Comparison of single and multiple trait selection strategies

As a means of comparing the progress made with each of the selection strategies applied in this thesis to the overall economic value of the resultant population, the b-values in Table 3.8 were multiplied by the mean population values for each of the four traits at the end of the fifth and tenth generations of selection. These index values are presented in Table 3.10.

In some cases very little change has taken place from generation five to generation 10, indicating that the limit to selection may have been reached soon after generation five. In all cases, index selection has resulted in greater improvements to the overall EV of the population than was achieved by any of the simulated single trait selection procedures. This demonstrates two principles: greater overall progress can be made with multiple trait

selection when some of the important traits are negatively correlated, and greater economic progress can be made when the economic value is considered in the selection process. Also of interest is the better progress made with family than with individual selection (IS) even with traits of high heritability.

Table 3.10 The value of the population, according to the cost economic values, after five and ten generations of selection using individual (IS), between family (BFS), within family (WFS), family-index (FIS) and index selection, and applied to the selection index equation

	Egg Weight		Egg Production		AFE		Body Weight	
Base population	65.97		65.97		65.97		65.97	
	Gen. 5	Gen. 10	Gen. 5	Gen. 10	Gen. 5	Gen. 10	Gen. 5	Gen. 10
IS	64.61	64.89	53.64	46.30	66.47	53.62	88.61	86.96
BFS	60.71	60.60	61.26	57.42	69.11	66.55	80.98	96.17
WFS	61.05	66.85	54.30	46.47	64.76	54.63	89.09	96.33
FIS	65.03	67.81	53.52	41.78	66.26	60.03	90.58	95.52
Index Selection	94.46	118.75	88.07	107.81	100.14	130.25	101.86	129.34

Of interest is the proportional change that has occurred to the index value over the 10 generations of selection. Selection for a particular trait does not guarantee an improvement to the index value, as is the case with most of the single trait selection strategies. The index value experiences a proportional increase after 10 generations of single trait selection for AFE with between family selection (BFS) (1.01), egg weight with within family selection (WFS) (1.01) and family-index selection (FIS) (1.03), and body weight with IS (1.32), BFS (1.46), WFS (1.46) and FIS (1.45). Under all other circumstances, the index value is decreased. This reveals the relative economic importance of each of the traits. Evidently improvement to body weight has a greater effect on the index value. The index value experiences an increase under index selection for each trait, but achieves an impressive proportional increase of 1.97 and 1.96 when applied to the specific improvement of AFE and body weight, respectively.

Further comparison of the progress made with each of the selection strategies is illustrated in Table 3.11. The mean value achieved in each of the four traits after 10 generations of

selection is illustrated to attain whether the selection index can achieve the same level of improvement as the single trait selection strategies. It is difficult to make a fair comparison as selection with the index is spread amongst more than one trait, which would compromise the progress achieved in a single trait. However, the largest proportional increase made in each trait from any of the different scenarios was used.

Table 3.11 The mean of egg weight, egg production, AFE and body weight in the base population, and after ten generations of selection, using individual (IS), between family (BFS), within family (WFS), family-index (FIS) and index selection

	Egg Wt	*Egg Prodn*	*AFE*	*Body Wt*
Base Population	**67**	**180**	**175**	**1800**
IS	78	189	152	2079
BFS	76	188	154	2056
WFS	78	191	151	2113
FIS	77	191	150	2108
Index Selection	73	191	148	2091

Index selection achieved a proportional increase in egg weight of 1.09, whereas both IS and WFS, the most successful single trait selection strategies, achieved a proportional increase of 1.16. However, the comparison does give unfair advantage to the single trait strategies, as egg weight is not given a large EV in any of the indexes and is therefore prevented from achieving any significant progress. The proportional increase achieved using index selection for egg production was 1.07, whereas FIS and WFS, the most successful single trait selection strategies, achieved an increase of only 1.06 by generation 10. Index selection for AFE achieved a value of 0.84 of the initial value (148 days), whereas FIS, the single trait strategy successfully selecting for the lowest AFE, attained a value of 0.86 of the former value (156 days). Index selection achieved a proportional increase of 1.16 in body weight, whilst WFS and FIS produced the largest increase for the single trait selection strategies and both achieved a proportional increase of 1.17. Further to the success of index selection, is its ability to simultaneously improve the values of other economically important traits.

Further scenarios could be investigated with the selection index with the aim of improving a primary trait whilst maintaining the value of the remaining traits. This was not the aim of this

exercise, which was concerned with the response of the selection index to varying production levels of egg production and body weight, however, if given more attention the selection index is without a doubt capable of more impressive results than those quoted above.

The SD of each of the four traits making the most progress under different scenarios of index selection, as discussed above, were compared to the SD of each of the four most successful traits of the single trait selection strategy. The SD associated with the largest value achieved in egg weight, egg production, AFE and body weight for index selection are 2.7, 5.0, 3.7 and 41.7, respectively, and 0.3, 3.2, 1.8 and 17.2, respectively, for single trait selection. Therefore index selection has a further advantage over single trait selection.

3.2.3 Discussion

It was stated earlier that selection using an index, ensuring the allocation of a suitable weight to each of the traits, will prove more effective than single trait selection (Hazel & Lush, 1943). The study of Yamada (1958) confirmed this, as did the results of the present study. The main factor reducing the ability of the single trait selection strategies is the existence of negative genetic correlations between the traits of economic importance. Manson (1972) expressed the view that simultaneous selection for various traits, having both positive and negative genetic correlations between them, may be worthless. Lerner (1958) believed that index selection has the ability to minimise the barrier formed by the genetic correlations. The theory of Lerner (1958) has proven accurate and illustrates the remarkable ability of the selection index to defy the invincible genetic correlations.

The response of each of the traits is dependent on the b-value assigned to it by the model. The b-values are determined by a combination of both genetic and economic values. Thus, it is important to understand the factors and their association that contribute to the b-values. Evidently, the larger the EV of a trait, the more emphasis that will be placed on producing a favourable b-value. However, there are also other factors influencing the b-values. Firstly, a high heritability will contribute to a larger b-value, as there is a greater chance of inheritance of the economically important trait. The relationship between the traits also contributes to the b-values. If a certain trait is given a large weighting, the traits positively correlated with that one will be boosted, however, traits negatively correlated with the trait of importance will receive a low b-value since they may compromise the success of that trait.

The b-values also control the success of the index. If the production levels of a certain trait are greatly increased, a large selection pressure will subsequently be applied to the trait. Under these circumstances the selection index can be compared to single trait selection as in theory only one trait is being selected for, having disregard for the values of the remaining traits. In these cases, the response of the trait may need to be restricted by manipulation of the b-values. An example of manipulation of the b-values is illustrated in Table 3.9 and Figure 3.8, where an attempt was made to simultaneously improve the value of egg production and body weight. However, in most cases it is used to regulate the values of those traits that are negatively affected by the course of selection. If the EV's have been chosen to represent that required by the customer then there should be no reason to

manipulate these further. Of course, as the performance of the population changes, and as the requirements of the customer change, so these EV's need to be altered, but because of the long-term effect of selection in improving the genotype of the breed or strain, frequent changes to the EV's would be counterproductive unless justified by significantly changed circumstances.

The selection index has proved to have many valuable features. Firstly, the selection index is capable of changing the resultant population by altering the EV's, allowing for accurate selection of the economically important traits. Zero weighting could be employed to ensure minimal alteration of certain traits, proving beneficial in maintaining the values of certain traits or preventing further deterioration due to negative correlations. An improvement could be achieved in two, rather significant, negatively correlated traits, namely egg production and body weight, proving that it is in fact possible to improve two of the most economically important traits simultaneously. The above results also illustrated that index selection is capable of reaching, and sometimes exceeding, the levels achieved by the single trait selection strategies. Further to its ability to positively influence the value of the primary economically important trait, it is able to simultaneously improve the value of other traits, based on the information supplied to it in the form of the b-values.

To add to the benefits of index selection is the ability of the strategy to maintain a reasonable SD, the importance of this having been discussed in Chapter 2. It would seem most likely that index selection is able to retain the SD of the main traits under selection due to its method of selection. Since the value of traits negatively correlated with the trait having the highest economic weighting also have the ability to be improved, a wide range of individuals will be selected. Selection would not be limited to only the best individuals according to one particular trait, but to those displaying favourable values for more than one trait. Hence the variation in the population is maintained.

Comparison of the single trait selection strategies with index selection, using the index value, illustrates the ability of index selection to maintain the economic worth of the population. Despite the inevitable deterioration in certain traits, the selection index is able to prevent a reduction in the value of the individual by maintaining or improving the value of other economically important traits. The index value of the single trait selection strategies produced such a varying response due to the different levels achieved in the trait under

selection, and the varying effect on the correlated traits to selection. Regardless, the value of index selection is beautifully illustrated, asserting itself as the best selection strategy and benefiting the performance of most traits, not just the one of most economic importance.

The results have convincingly illustrated various ways in which index selection is superior and provides better results than single trait selection. In summary, the selection index has proved capable of counteracting negative genetic correlations, matching the levels of the traits, and in some cases exceeding them, achieved by the single trait selection strategy, whilst effecting a simultaneous improvement to other economically important traits, conserving the SD of the economically important traits to ensure reasonable progress can be achieved for longer periods of time and maximising the value of the population according to the EV of the traits used in the index equation. Therefore, it is clear that index selection is the most successful selection strategy and should be the strategy of choice in any selection exercise. Hence the selection index has proved to be a true feat and an invaluable discovery to the broiler industry.

CHAPTER 4

GENERAL DISCUSSION

The objective of my study was to determine to what extent it may be worth trying to increase egg production in broiler breeders whilst retaining the rapid growth rate in the progeny, considering that these traits are negatively correlated. Following Chapter two, this seemed an impossibility, however, the selection index discussed in Chapter three, proved the possibility of simultaneous improvement of these two traits.

Single trait selection has been the strategy of choice in the past and has certainly been of benefit to the broiler industry as it has allowed for the vast improvements that have been achieved in growth traits. However, there are various traits that now demand attention due to their growing economic importance. Examples of such traits are skeletal quality, heart and lung function, welfare traits, robustness and reproductive traits (McKay, 2008). Multiple trait selection has thus become the strategy of choice for the broiler industry. Focus should now be placed on maintaining the improvements that have been made in growth rate and allow other traits the possibility of improvement.

Although the truth of deteriorating reproductive traits of the breeding generation has been exposed and proved, and the importance of improvement to these traits has been stated; the factor that sets the broiler industry apart from the laying industry is the radical protein producing machine that the broiler has become. Realistically, removal of the emphasis placed on growth traits is unlikely to occur due to the economic implications to the industry and the progress that is still achieved in this trait. Geneticists will remain devoted to growth traits in their breeding programmes whilst attempting to minimise the negative effects on reproductive traits (Pollock, 1999). A significant decline in reproductive efficiency, more than 20%, will effect a change to the standard way of thinking.

Apart from the deterioration of reproductive and liveability traits due to the selection of growth traits, future improvements to growth traits will also be limited due to other factors (Professor R.M. Gous, 2009, Pers. Comm.[7]). These include the size of the egg from which the chick

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[7] Professor R.M. Gous, University of KwaZulu-Natal, gous@ukzn.ac.za

hatches, the issue of supplying sufficient protein to day-old chicks given their increased amino acid requirements, and the reduction in ability of the fast-growing broilers to lose enough heat to the environment to allow for potential growth rate. Given the popularity for research of all avenues to further the success of the broiler, each case has been researched in an attempt to reduce the limitations.

Firstly, egg weight could be increased by selection, however, the negative genetic correlation of egg weight with egg production would place a further burden on egg production, which has a higher EV than egg weight, removing this possibility for improvement (Professor R.M. Gous, 2009, Pers. Comm.[7]). Early access to feed and *in ovo* feeding can also alleviate the constraint of the egg on embryonic development, however, only to an extent. The reduction in ability of fast-growing broilers to dissipate heat in the later stages of the growing period is coupled with rising environmental temperatures and energy costs. There are various dietary methods to alleviate this problem, although few have provided workable solutions, proving heat dissipation of fast-growing strains to be the most challenging factor in the foreseeable future.

Given that more and more traits are growing in economic importance, and some are not easily measured, technological advancements are required in the selection methods used. One such advance is the use of gene markers through Single Nucleotide Polymorphisms (SNP). These may be used to accurately identify individuals for multiple economically important traits at the DNA level. The need for older selection strategies is however not removed. Markers are used to select the optimum individuals who are then exposed to conventional, multiple trait selection strategies.

Constant economic evaluation of traits involved directly and indirectly with broiler meat production is crucial. Furthermore, modelling of the traits to multiple trait selection in order to determine their response and interaction with one another is imperative to assist future decision making. Hence a study such as this will never lose its economic value.

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