Evaluation of Sources of Error in Weight Records of Commercially Raised Growing Pigs

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I hereby certify that the thesis has not been submitted for a higher degree at any University or Institution, and work embodied in this thesis is my work unless noted otherwise in the acknowledgements.

Birgit Schauer

This thesis is dedicated to Karl Hammer, who has been a source of inspiration to me for many years

Abstract

The objective of this research was to investigate sources of errors in pig weight measurements. Three studies were conducted using data from one commercial New Zealand pig farm. In Chapter 4, finisher pigs fed ad libitum or via a computerized liquid feeding system were weighed four times a day over a four-day period. Results showed that standardization of weighing time reduced diurnal fluctuations in pig weight. However, multivariate analysis showed that there was a significant interaction between day and time of day, which indicates that diurnal fluctuations in live weight are not consistent between days, particularly in ad libitum fed pigs. Hence, Chapter 5 investigated whether overnight feed withdrawal for 11 hours (weaners) or 17 hours (growers and finishers) is effective in reducing between-pig variation in live weight and growth rate. For grower and finisher pigs, feed withdrawal was associated with a reduction in variability in live weight and growth rate by up to 11.5%, whilst the effect was inconsistent in weaner pigs. It is recommended to repeat the investigation on other farms to assess long-term effects on pig performance before general recommendations can be made.

Chapter 6 compared the magnitude of sampling error when sampling pens from batches of pigs, using different sample sizes and sampling methods. Increasing the portion of randomly selected pens reduced the sampling error, but in a diminishing manner. Purposive selection of two pens reduced sampling error by more than 64% compared with random sampling. However, purposive sampling introduces the risk of obtaining biased estimates. Thus, it is recommended to select pens from batches at random. These results may be used as an educational tool to demonstrate how to minimize errors in pig weights. Collecting more accurate weight records is likely to lead to improved interpretability of pig weights, and may promote better use of production data.

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[1] At http://edoc.ub.uni-muenchen.de/archive/00006596/01/Schauer_Birgit.pdf

1BAcknowledgements

Abbreviations

ADG	Average daily gain, growth rate (kg/d)
AIC	Akaike's information criterion
AL	Ad-libitum (feeding system)
AR(1)	First order Autoregressive covariance term
CI	Confidence interval
CL	Computerized liquid (feeding system)
CV	Coefficient of variation
d	Day(s)
df	Degrees of freedom
IQR	Interquartile range
kg	Kilogram(s)
ln	Logarithm to the base of e (natural logarithm)
MJ	Mega joule
ML	Maximum likelihood
n	Number or sample size
P	P-value
R^2	Squared correlation, R-squared value
RMSE	Root-mean-squared error
SD	Standard deviation
SE	Standard error
Wgt	Weight

2BAbbreviations

Table of Contents

Table of Tables

Table of Figures

Chapter 1 Introduction

An effective monitoring system offers several opportunities to optimize profit in the growing pig herd. The growing herd has a large impact on overall farm profitability (Holtkamp, 1999), which may be explained by the high proportion of feed cost expended in this production unit. Therefore, accurate decision-making may be even more important in the growing herd than in the breeding herd. However, it appears that commercial farms have been less successful in monitoring the growing than the breeding herd.

A nationwide survey was conducted in 2000 on 94% of US pig herds keeping 100 or more pigs (United States Department of Agriculture, 2002). Results from this survey showed that 76.2% of sites with breeding animals kept breeding records, however only 17% and 19% of sites with grower/finisher pigs were able to calculate average daily gain and feed efficiency, respectively. More than half the sites had no information on growth rate (56% of sites) or feed efficiency (62% sites) for the growing herd, whilst the remainder of sites provided estimates. Similarly, Deen and Wattanaphansak (2002a) summarized results from an informal survey as follows:

A fraction (of swine producers) had accurate estimates of days to market, fewer had estimates of feed conversion, yet most could estimate their sows' reproductive performance.

Hence, both surveys indicate that the same producers may collect detailed breeding herd records, but little or no growing herd records. This may indicate differences in the ease of data collection and interpretation of records between the growing and breeding herds. To the author knowledge, there is a lack of studies evaluating the use of performance records on New Zealand pig farms.

Pig weight measurements represent key performance parameters in the growing pig herd. Pig weights are used on their own, for instance when making marketing decisions, or after calculation of indirect parameters such as growth rate and feed efficiency. Hence, accuracy of pig weights has a large impact on the effectiveness of the monitoring system. It was conjectured that a better understanding of factors causing errors in pig weights would enhance the interpretability of records, and may thus contribute to an increased adoption of growing herd monitoring.

The objective of this thesis was to investigate sources and magnitude of errors in pig weights of commercially housed growing pigs. All data were derived from one commercial New Zealand pig farm, which is described in Chapter 3. Chapter 4 investigates the effect of time of day on live weight of finisher pigs. This information was used to assess if standardizing weighing time could reduce error in pig weights due to variation in biological factors such as gut fill. Chapter 5 evaluates whether overnight feed withdrawal may reduce between-pig variation in live weight and growth rate by reducing variability in gut fill. Chapter 6 compares the magnitude of the sampling error between (1) different sample sizes following random sampling, and (2) random sampling and purposive sampling when sampling two out of eight pens. The thesis concludes with a general discussion of the results. Cited references are listed at the end of the thesis.

Chapter 2 Literature Review

2.1 Introduction

Modern, intensive pig production is a business with the primary goal of maximizing profit (Radostits, 2001). Pig producers have various opportunities to manipulate diet, environment, and health. However, the presence of many interrelated factors affecting pig performance makes it difficult to determine the most cost-effective optimization strategy (Deen, 1998; Polson et al., 1998). A monitoring system may assist producers to develop such a strategy, as it helps them to understand the factors driving performance and profit. Hence, the development of an effective monitoring system should be viewed as essential in the successful management of a pig unit (Jalvingh, 1992; Deen, 1994; Radostits, 2001).

Two production systems can be distinguished in pig production: (i) the breeding pig herd and (ii) the growing pig herd. Monitoring the growing herd should be emphasized as this is the production unit that has the most influence on profitability (Holtkamp, 1999; Deen and Wattanaphansak, 2002a; Dial and Rademacher, 2005). Common performance parameters assessed in the growing herd are daily feed intake, growth rate, feed efficiency, mortality rate, and carcass weight sold per pig space per year (throughput) (Dial and Rademacher, 2005). Collection of these parameters appears relatively simple. However, in practice, collecting accurate growing herd data and utilizing the information effectively has been a challenge for producers (Deen and Wattanaphansak, 2002a; Dial and Rademacher, 2005).

Two problem areas have been repeatedly associated with the underutilization of performance monitoring in the growing herd (Deen, 1994; Radostits, 2001; Dial and Rademacher, 2005). First, routinely collected growing herd records tend to provide insufficient detail to evaluate production changes. Secondly, it is difficult to interpret growing herd production data because the relationship between production parameters is not well understood. To date, little research has been conducted to investigate methods to improve the process of growing herd performance monitoring on commercial farms.

The objective of this review was to describe the monitoring process in the growing pig herd and provide an overview of data, which can be collected in the growing pig herd. This chapter concludes with an outline of sources of errors and bias.

2.2 Areas of monitoring

Farm management may be described as the allocation, direction, and control of limited resources to achieve the goals of the farm efficiently (Olson, 2004). Monitoring is considered an integral part of farm management as it provides quantitative data for decision-making (Jalvingh, 1992; Deen, 1994; Polson et al., 1998; Dial and Rademacher, 2005). Monitoring may be defined as the making, recording, and transmission of routine observations on health, productivity, and environmental factors (Thrusfield, 2005). Kyriazakis and Whittemore (2006) described objectives of records to monitor production performance as follows:

- to provide information about the present status of performance,
- to provide information about the past performance,
- to provide a basis for production management by allowing the diagnosis and solving of problems, and
- to provide factual data to allow considered forward policy planning.

When developing a monitoring system, producers and/or consultants need to consider what outcomes they expect from the system, what information they can collect, and how the data will be interpreted and utilized. Areas where monitoring can be applied in the growing pig herd include the development of budgets and targets, problem detection, effective utilization of resources, inducing change, and forward planning. The remainder of this section addresses each of these areas in more detail.

2.2.1 Developing budgets and targets

Developing and implementing a strategic plan for a business requires budgets and targets to be set. Budgets report the quantified estimates of expected results due to carrying out a specific plan or set of actions (Olson, 2004), and may be used to forecast financial performance (financial budgeting). Targets are performance levels that could be achieved under favourable conditions. Budgets and targets may be developed for performance measures of both central tendency (e.g. mean) and variability (e.g. standard deviation).

Budgets and targets may be established using historical data derived from the own farm, performance data of other farms (benchmarking), and/or theoretical knowledge (Polson et al., 1998). Historical data are helpful in estimating the production capacity of the farm, whereas production data from other farms and theoretical knowledge may highlight opportunities for improvement. For instance, to assess opportunity costs due to endemic disease, benchmarks could be set using data from high health herds. Benchmarking systems generally include a large number of commercial producers, possibly selected as they share similar facilities. However, benchmarking systems can be inaccurate or misleading due to factors such as lack of standardized parameter calculations, overall deficiencies in data quality, and presence of unknown confounding factors (Reeves, 2000; Hill, 2001; Lowe, 2003). Hence, in order for the benchmarking process to be beneficial, producers need to have a good knowledge of their own farm performance, identify a good source for benchmarking information, study the other systems, and learn from them (Reeves, 2000).

After budgets and targets have been established, actual performance is measured against these budgets and targets to indicate whether corrective actions are required. It may be necessary to revise budgets and targets at regular intervals to address changing circumstances. Several reports exist of how budgets and targets may be applied to assist decision-making (MacDougald, 1999; Hill, 2001; Dial et al., 2003). Budgets and targets are be best achieved by combing several strategies such as problem detection, effective utilization of available resources, implementing changes to the current system, and forward planning. These strategies are described in the following sections.

2.2.2 Problem detection

Continuous evaluation of production records allows problems to be addressed immediately thus avoiding unnecessary production losses. However, such a system is conditional on the collection of production data and correct and timely interpretation of that data. To assist in the process of problem detection and problem solving it would be desirable to have a series of clearly defined diagnostic steps. Morris (1982) suggested the concept of "performance-related diagnosis", where performance indicators are used to determine whether observed production levels are within expected ranges. If a problem is present, diagnostic indicators help identifying potential causes of poor performance. Classical performance indicators in the growing herd are growth rate, feed efficiency, and mortality rate. Deen and Wattanaphansak (2002a) suggested attrition cost would be more indicative of financial success than mortality. Attrition refers to the number of pigs in a group not meeting the targeted market weight, and includes deaths, culls, and light pigs. Measuring attrition enables producers to identify the opportunity cost that is, the difference between actual and potential revenue.

The challenge in problem detection is to distinguish between random variation and variation due to assignable causes. Enhancing the accuracy of production records reduces random variation, thus leading to records of higher diagnostic value. Differentiation between random variation and variation due to assignable causes (production problems) is facilitated by the use of statistical methods such as control charts (Reeves, 2000; Yeske, 2002). For instance, control charts have been applied to determine significant production changes in finisher pigs (Rademacher, 2004) and in breeding sows (Krieter et al., 2005).

2.2.3 Effective utilization of available resources

Production records may be used to optimize the balance between inputs and outputs given the currently available resources. Three examples are provided indicating how production records may facilitate optimum utilization of resources: (i) controlling pig flow, (ii) developing marketing strategies, and (iii) optimizing the feeding regime.

Controlling pig throughput

Variability in pig throughput has a large impact on profitability (Vantil et al., 1991). Therefore, controlling variability in pig throughput ensures that the output of the farm is close to optimum. A common measure of throughput is kilograms sold per pig space per year, which can be determined using sales records. However, when the aim is to identify and control sources of variability in pig throughput, both breeding and growing herd performance needs to be monitored. In the breeding herd, sources of variability in pig flow are variability in numbers of piglets weaned and weaning weight. Diagnostic indicators for low weaning numbers are number of breeding females served per week, farrowing rate, litter size, and pre-weaning mortality rate (Hunsberger, 1999). Records of weaning age, birth weight, and within-litter birth weight variation may serve as diagnostic indicators for problems associated with suboptimal weaning weight (Pluske et al., 2003a). In the growing herd, diagnostic indicators of changes in pig throughput are mortality rate and growth rate for either the entire growing period or individual production stages.

Developing marketing strategies

Towards the end of the production period, producers must decide when to sell the pigs. The choice of the marketing strategy has a large impact on annual profit (Deen, 1998; Greenley, 1999). An individual pig reaches optimum market weight when the margin over feed cost is maximized that is, the gain in revenue for additional weight is no longer greater than the increase in feed cost (Dritz et al., 1997; Greenley, 1997; Smith, 2003). Sort loss occurs if a pig is marketed at a weight that is either above or below optimum weight. In general, the relative loss from marketing pigs at a heavier weight than the optimum is lower than that from marketing pigs at lighter than optimum weight (Deen, 1999a).

Optimum market weight may be determined by expected pig performance and financial information (Deen, 1999a). Expected pig performance includes growth performance, feed efficiency, and carcass characteristics. Each of these three performance measures can be described as a function of either time or weight. Several authors (Caldwell, 1998; Deen, 1998; Dritz and Tokach, 1998) have demonstrated the use of growth curve analysis to estimate optimum market weight. Feed cost and carcass pricing grid represent the only financial information required since short-term marketing decisions can ignore fixed costs (Deen, 1998).

When pigs are managed in batches (all-in, all-out management), variation in market weight and premiums paid for uniformity in market weights prevents many producers from marketing an entire batch at one time. Therefore, a batch is generally marketed in several lots. This process of splitting a batch is termed split marketing (Scroggs et al., 2002). However, building constraints generally impede marketing all pigs of a batch at optimum weight. Therefore, the following rule is considered effective when applying split marketing to a batch of pigs (Dritz et al., 1997; Greenley, 1997): Initially, the aim is to sell pigs close to their optimum market weight. However, as soon as production capacity becomes limiting, all remaining pigs of a batch are sold to facilitate optimum production throughput. The advantage of split marketing is that it may reduce production costs by lowering total feed costs and improve income as a greater proportion of pigs is marketed at optimal weight (Deen, 1998; Scroggs et al., 2002). However, buildings are utilized to a lesser extent than marketing the entire batch at the same time, since all-in, all-out locations can only be re-filled after the last pig has been sold.

Optimizing the feeding regime

Altering the amount and composition of feed supplied is the most effective means of controlling growth rate and the efficiency of growth. Furthermore, financial losses occur if nutrient intake of an individual pig exceeds its requirement. For instance, overfeeding lysine by 0.1% was estimated to increase feed cost per pig by approximately US$ 1.20 (Goodband et al., 2001). Knowledge of nutrient requirements at different stages of growth facilitates formulating cost-effective diets. However, most published nutrient requirements have been derived from pigs raised in a research environment. On commercial farms, both feed intake and nutrient utilization are likely to be altered by the presence of a variety of stressors (Wellock et al., 2003; Nyachoti et al., 2004). Hence, on-farm measurements may provide farm-specific estimates of nutrient requirements, thus facilitating formulation of more adequate, cost-effective diets.

The three main factors affecting nutrient requirements of growing pigs are live weight, protein deposition rate, and feed intake (De Lange, 1999a). These parameters change dynamically as pigs grow older, so that serial measurements are required to determine changes in nutrient requirements over time. Several authors have proposed ways how to establish feed intake, growth, and lean gain curves on commercial farms (Smith et al., 1999; De Lange, 1999a; De Lange et al., 1999b). Farm-specific nutrient requirements can then be estimated from the feed intake, growth, and lean gain curves using growth models and optimization algorithms (Moughan et al., 1995; De Lange et al., 2001).

2.2.4 Planning, implementing, and controlling change

In response to changes in conditions, technology, and economic factors, a pig unit needs to be improved and upgraded to remain competitive. The current system of a production unit may be improved in several ways such as upgrading housing facilities, adopting new technologies, change in genetics, or reducing the impact of endemic diseases. Monitoring pig performance may assist in both planning the change and monitoring the effectiveness of the change.

When planning a change, performance records may be of use in identifying potential changes and prioritizing changes according to the expected cost-effectiveness and risk of failure. After a change has been applied, one should verify if the change was successful by comparing performance before and after the intervention. For instance, several studies exist that document changes in herd performance before and after the implementation of a partial depopulation to eradicate Mycoplasma hyopneumoniae on New Zealand pig farms (Frey et al., 1998; Lawton, 2000; Schauer et al., 2006). However, a comparison of before- and after-performance is insufficient to prove causation, since a control group does not exist. Other factors may have changed over time, thus biasing differences between before- and after-performance. Therefore, it is important to control for potentially confounding factors. to reduce confounding bias. Furthermore, statistical power analysis should be applied to determine adequate sample sizes that allow detecting significant differences between before- and after-performance (Lowe, 2003).

2.2.5 Forward planning / risk management

Pig production is associated with risk as it requires a high level of inputs and relies on returns from consistent outputs. Hence, the ability to manage risk is considered an important factor for the long-term sustainability of a modern pig unit (Radostits, 2001; Australian Government Productivity Commission, 2005). Risk is the chance of something happening that will have an impact on objectives (Standards Australia and Standards New Zealand, 2004). In a survey of 630 US pig farms conducted in 2000, pig producers rated unfavourable production changes (production risk) amongst the three highest risks, besides pig price variability (market risk) and changes in environmental regulations (legal risk) (Patrick et al., 2000). Possible sources of production risk in agriculture are disease introduction, failure of technology, changes in genetics, and the quality of inputs (Olson, 2004).

Risk management is the culture, processes, and structures that are directed towards realizing potential opportunities whilst managing the possibility of adverse effects (Standards Australia and Standards New Zealand, 2004). Before, implementing a risk management strategy, one must first assess the risk using qualitative, semi-quantitative or quantitative methods. Monitoring growing herd performance provides numerical values of past and current performance that can be used in the risk assessment process. Using the monitoring data, one can also determine the sources of uncertainty that could be investigated further in a quantitative assessment, using a stochastic approach. Reducing variability in pig performance reduces the uncertainty of risk, thus increasing the predictability of risk. Hence, both monitoring and controlling variability of production parameters may be regarded as a means of risk reduction (Webster, 2002).

2.3 Performance measures as a means to assess the effect of external factors on growth performance

Pig performance is influenced by a range of factors that can be categorized as related to the animal, the diet, the environment, the management, and health.

Factors that contribute to reduced animal performance represent risk factors for production problems (Dohoo et al., 1997). Factors affecting pig performance have been widely investigated in experimental research (Table 2.1). However, animals in experimental research are generally kept under ideal health and environmental conditions (e.g. no disease, individual housing, optimum temperature) to minimize confounding effects. While experimental studies provide valuable information, pigs may respond differently when raised under commercial conditions. For instance, Holck *et al.* (1998) measured back fat and growth in 48 barrows between 30 and 120 kg live weight that had been randomly assigned to either a commercial or unrestricted research environment. Pigs in the unrestricted environment were housed in a separate airspace from other pigs under thermoneutral conditions and were provided with a higher floor space allowance than pigs in the commercial environment. Repeated weight and back fat measurements revealed that growth rate and protein accretion were approximately 30% lower in pigs raised in the commercial operation than in pigs raised in the research environment. Consequently, associations between factors and animal performance derived from experiments may not be directly applicable to commercial situations without obtaining additional on-farm measurements.

In contrast to experimental environments, pigs raised under commercial conditions are subjected to multiple, concurrent stressors, which makes it difficult to assess the effect of individual stressors. For instance, Hyun *et al.* (1998b) assigned grower pigs (n = 256) to a 2 × 2 × 2 factorial arrangement assessing the effect of stocking density (0.25 m^2/pig versus 0.56 m^2/pig), regrouping (regrouped or static group), and cyclic temperatures (diurnal temperature cycling from 28 to 34°C or thermoneutral 24°C) on growth performance. Each stressor alone depressed feed intake, growth rate, and feed efficiency. The study found a linear, negative relationship between the number of stressors imposed and the three performance parameters. Hence, the study concluded that the effect of multiple stressors is additive. The same study suggested that the additive effect of multiple stressors can possibly be predicted if the effect of individual stressors is known. Similarly, McFarlane *et al.* (1989) found a linear decrease in chicken performance when increasing the number of stressors from one to six. On the contrary, Kerr *et al.* (2003b) found that the effects of *Actinobacillus pleuropneumoniae* challenge and changes in ambient air temperature (15 or 30°C) on pig performance were not equally additive since the effects of the disease treatment were more profound than the effects of temperature. This divergence between study findings may suggest that if at least one out of multiple stressors is severe (e.g. acute disease challenge), the effect of other milder stressors on animal performance may be less apparent.

On commercial farms, it is generally not feasible to determine the direct effect of external factors. Instead, it is common practice to monitor animal attributes, such as animal weights, mortality, and feed intake. Animal attributes reflect the animal's response to its environment. Hence, combining accurate on-farm measurements with the knowledge from research allows producers and consultants to estimate the farm-specific effect of external factors on animal performance. If performance parameters are then coupled with accurate records of when changes are made to external factors (e.g. diet changes, treatment regimes), it is possible for producers to make informed decisions about the effectiveness of interventions.

Table 2.1. Summary of experimental studies (E), reviews (R) and simulation models (M) investigating the effect of factors on post-weaning pig performance such as growth rate, feed intake, feed efficiency, mortality rate, and carcass composition.

Factor group	Description	References
Animal		
	Gender	Thompson *et al.* (1996) (E); Xue *et al.* (1997) (R); van Lunen and Cole (1998) (E); Chang *et al.* (2000) (E); Dunshea *et al.* (2003) (E); Pluske *et al.* (2003b) (E); King *et al.* (2004) (E)
	Genotype	Smith and Pearson (1986) (E); de Haer and Devries. (1993a) (E); Kyriazakis *et al.* (1994) (E); Cameron and Curran (1995) (E); Affentranger *et al.* (1996) (E); Thompson *et al.* (1996) (E); Fabian *et al.* (2003) (E); Fabrega *et al.* (2003) (E)
	Birth weight	Quiniou *et al.* (2002) (E); Wolter *et al.* (2002a) (E)
	Weaning weight	Mahan and Lepin (1991) (E); Wolter and Ellis (2001a) (E); Dunshea *et al.* (2002) (E); Dunshea *et al.* (2003) (E); Pluske *et al.* (2003b) (E)
	Age	Shields *et al.* (1983) (E); Thompson *et al.* (1996) (E); van Lunen *et al.* (1998) (E); Lebret *et al.* (2001) (E); Fabrega *et al.* (2003) (E)
Diet		
	Diet composition	Castell and Cliplef. (1991) (E); Chiba *et al.* (1991) (E); Susenbeth (1995) (R); Friesen *et al.* (1996) (R); Baker (2000) (R); Whittemore *et al.* (2001) (R); Weatherup *et al.* (2002) (R); Kerr *et al.* (2003a) (E)
	Grain-based diets versus by-product feeding	Westendorf *et al.* (1998) (E); Myer *et al.* (1999) (E); Chae *et al.* (2000) (E); Kjos *et al.* (2000) (E); Moon *et al.* (2004) (E)
	Feed processing (e.g. milling, pelleting, heat processing)	Walker *et al.* (1989) (E); Chae and Han. (1998) (R); Chu *et al.* (1998) (E); Laitat *et al.* (1999) (E); Yang *et al.* (2001a) (E); Yang *et al.* (2001b) (E); Ohh *et al.* (2002) (E); Choct *et al.* (2004) (E)
	Feeding form (dry, liquid, wet-dry)	Andersson *et al.* (1997) (E); Chae *et al.* (1997) (E); Gonyou and Lou (2000) (E); Yang *et al.* (2001a) (E); Yang *et al.* (2001b) (E); Choct *et al.* (2004) (E)
Environment		
	Group size	De Haer and Devries (1993b) (E); Gonyou *et al.* (1992) (E); Nielsen *et al.* (1995) (E); Spoolder *et al.* (1999) (E); Bornett *et al.* (2000) (E); O'Doherty and Keon (2000) (E); Hyun and Ellis (2001) (E); Wolter *et al.* (2001b) (E); Hyun and Ellis (2002) (E); Schmolke *et al.* (2003) (E); Turner *et al.* (2003) (R); O'Connell *et al.* (2004) (E); Turner and Edwards (2004) (R)

Factor group	Description	References
	Floor space allowance	Heitman *et al.* (1961) (E); Kornegay and Notter (1984) (R); Edwards *et al.* (1988) (E); Pearce and Paterson (1993) (E); Gonyou and Stricklin (1998) (E); Hyun *et al.* (1998a) (E); Ferguson *et al.* (2001) (E); Edmonds and Baker (2003) (E); Hamilton *et al.* (2003) (E); Morrison *et al.* (2003) (E); Leek *et al.* (2004) (E); Smith *et al.* (2004) (E); De Decker *et al.* (2005) (E)
	Feeder space	Walker *et al.* (1991) (E); Spoolder *et al.* (1999) (E); Korthals (2000) (E); Georgsson and Svedsen (2002) (E); Turner *et al.* (2002) (E); Morrison *et al.* (2003) (E); Laitat *et al.* (2004) (E)
	Air quality	Donham (2000) (R); Murphy and Cargill (2004) (R); Wathes *et al.* (2004) (E); Lee *et al.* (2005) (E)
	Climate (e.g. temperature, humidity)	Lopez *et al.* (1991a) (E); Lopez *et al.* (1991b) (E); Rinaldo and Le Dividich (1991) (E); Hessing and Tielen. (1994) (E); Le Dividich and Herpin (1994) (R); Granier and Massabie. (1996) (E); Quiniou *et al.* (2000) (E); Kouba *et al.* (2001) (E); Le Bellego *et al.* (2002) (E); Kerr *et al.* (2005) (E)
Management		
	Mixing / regrouping	Hessing *et al.* (1994) (E); Stookey, and Gonyou (1994) (E); Hyun *et al.* (1998a) (E); Brumm *et al.* (2002a) (E); Leek *et al.* (2004) (E); Kerr *et al.* (2005) (E)
	Moving	Hessing *et al.* (1994) (E); Brumm *et al.* (2002b) (E)
	Sizing	O'Quinn *et al.* (2001) (E); Wolter *et al.* (2002b) (E)
	Weighing	Augspurger *and Ellis* (2002) (E); Wolter *et al.* (2002c) (E)
Health [a]		
	Enzootic pneumonia (Mycoplasma hyopneumoniae)	Straw *et al.* (1989) (R); Clark *et al.* (1993) (E); Maes *et al.* (1996) (R); Desrosiers (2001) (R); Miller *et al.* (2001) (M); Escobar *et al.* (2002) (E)
	Pleuropneumonia (Actinobacillus pleuropneumoniae)	Straw *et al.* (1990) (E); Kerr *et al.* (2003b) (E)
	Proliferative enteropathy (Lawsonia intracellularis)	Lawson and Gebhart (2000) (R); Boesen *et al.* (2004) (E); Paradis *et al.* (2004) (E); Whitney *et al.* (2006) (E)
	Swine dysentery (Brachyspira hyodysenteriae)	Hampson and Trott (1995) (R); Siba *et al.* (1996) (E); Durmic *et al.* (2002) (E); Pluske *et al.* (2002) (R); Lindecrona *et al.* (2003) (E)
	Sarcoptic mange (Sarcoptes scabiei)	Davies. (1995) (R); Bornstein *et al.* (2004) (R)

[a] Addressed are only the most common health problems found in New Zealand.

2.4 Data collection in the growing pig herd

2.4.1 Pig flow

Typically, a growing herd does not operate under a system that identifies individual pigs. Instead, the interest lies in monitoring herd, shed or group performance. The nature of pig flow on a farm determines at what level data can be recorded.

Growing pigs are generally grouped at different levels such as sites, buildings, rooms, and pens. In New Zealand, growing pigs are traditionally reared on the same site using a three-stage production system: (i) weaner (also called nursery) stage, (ii) grower stage, and (iii) finisher stage (Figure 2.1). Generally, pigs are managed as weaners until approximately 25 to 30 kg live weight, as growers until 50 to 60 kg live weight and as finishers up to market weight, although this may slightly vary between farms.

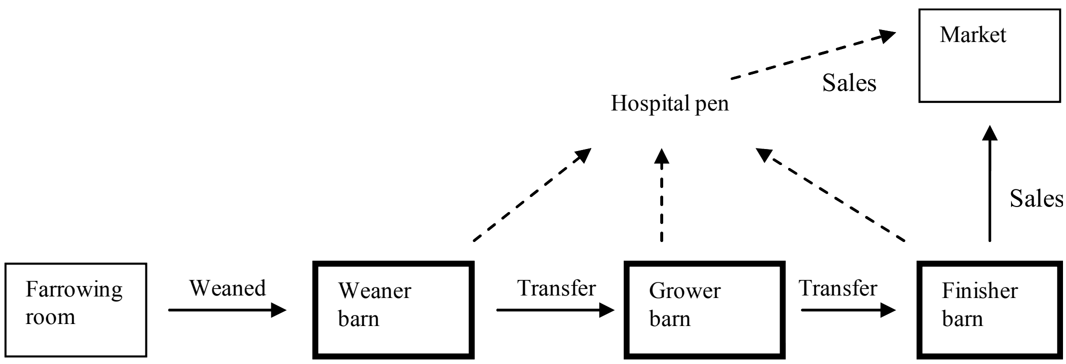

Figure 2.1. Characteristics of a three-stage growing herd production system on a typical New Zealand pig farm. Solid lines denote batch movements, whilst dashed lines indicate movements of individual pigs that have been separated from the batch prior to market.

Pigs at each production stage may be managed throughout production using an all-in, all-out or continuous flow system. Continuous flow system is the traditional management system where pigs enter and leave a shed depending on their weight without regard to maintaining group integrity. As a result, sheds may house pigs with an age spread of several weeks. This type of facility flow has the advantage that it maximizes space utilization and requires a minimum amount of planning.

More recently, all-in, all-out management has been introduced, whereby groups of pigs of approximately the same age ('batches') enter and leave a room, building or site as a cohort group. The essential component of all-in, all-out management is that each location is thoroughly cleaned, disinfected, and left empty for several days between batches.

The advantage of applying all-in, all-out compared to continuous flow management lies in the reduction of disease transmission and concurrent improvements in growth performance. This was shown by Kendall *et al.* (2000) who compared growth performance of pigs either placed in continuous flow (n = 192) or all-in, all-out facilities (n = 168) between 49 days of age and market. Growth rate was 11.8% and feed efficiency was 5.3% higher for all-in, all-out pigs than for continuous flow pigs (P > 0.001). Similarly, Scheidt *et al.* (1990) reported 9.0% higher growth rates when pigs were reared in an all-in, all-out environment (n = 96) compared to pigs reared in a continuous flow environment (n = 96).

With increasing specialization, all-in, all-out management has gradually replaced continuous flow management of growing pigs. This trend was shown by three national US surveys conducted in 1990, 1995, and 2000 (National Animal Health Monitoring System, 2005). The samples used for the surveys represented 91% to 95% of US producers. On sites with 100 or more grower/finisher pigs, the percentage of pigs managed as all-in, all-out increased steadily from 31.4% in 1990 to 84.5% in 2000. Larger sites were more likely to adopt all-in, all-out management than smaller sites. Thus, the percentage of sites managing pigs all-in, all-out showed a more gradual increase (24.9% in 1990, 40.0% in 1995, and 56.9% in 2000) than the percentage of pigs being managed as all-in, all-out.

In contrast, a 1995 abattoir survey of risk factors for respiratory diseases on New Zealand pig farms with more than 100 pigs found that only 30.3% of the 89 farms managed grower/finisher pigs as all-in, all-out (Stärk, 1998). Whilst the response rate was 37.2% (n = 116), data analysis was limited to 89 farms as three remote abattoirs could not be included in the study. The median number of sows on the surveyed farms was 124 (first quartile: 84 sows; third quartile: 200 sows). The US survey reported frequency tables, but not the median number of sows per farm. However, other survey using PigCHAMP databases of US farms indicate that the average female pig inventory of US pig farms generally comprises 400 or more sows (King et al., 1998; Straw et al., 1998). Smaller herd sizes of New Zealand compared to US farms may have contributed to the slower adoption of all-in, all-out management, since continuous flow economizes building costs for small herds (Dobbinson, 2000).

Besides general health and performance benefits, all-in, all-out production offers advantages in performance monitoring. In continuous flow systems, the population is continuously changing without any start or endpoint. Hence, data can only be collected at the shed level. Unless pigs are individually identified, the time individual pigs stay in a continuous flow location is unknown resulting in production records of little diagnostic value (Polson et al., 1998). In contrast, all-in, all-out management allows producers to monitor groups of pigs (batches) individually.

Batch-level data provide more detailed information than shed level data, thus offering benefits in the identification of production problems and the evaluation of intervention strategies. Traditionally, the focus of performance monitoring was to assess batch averages. One problem with focussing on averages is that the costs of variation cannot be determined (Deen, 1999b). Therefore, there has been increasing emphasis on monitoring variation as well as average performance (Holtkamp, 1999; Patience et al., 2004; Taylor and Roese, 2006).

Monitoring variation may assist in enhancing farm profitability in several ways. For instance, controlling variability is essential when the aim is to maximize throughput (Yeske, 2000), develop cost-efficient diets (Knabe, 1996; Dritz, 2004), and optimize market return (Deen et al., 2002b). Additionally, monitoring and controlling variation provides a means of risk reduction (Webster, 2002). However, measuring variation can be a cumbersome task, as it requires individual pig measurements. Variation in growth rate from birth to market (carcass growth rate) may be calculated if individual carcass weights are available, pig age is known, and dressing percentage is assumed constant. Hence, carcass growth rate may be used as a simple means to monitor end-point variation in pig performance. When variation is derived from on-farm measurements, sampling may be used to reduce the workload of obtaining individual pig measurements for all the pigs in a single batch. However, it is important to select an appropriate sampling technique and sample size to obtain the desired information at a minimum cost.

Variation can be expressed in different ways. Standard deviation (SD) is a common measure of variation if data are normally distributed. Approximately 66% of values will fall within one SD either side of the mean, 95% within two SD, and 99% within three SD (Radostits, 2001). The coefficient of variation is a useful measure of variation when comparing batches, as it is adjusted for the mean. If data are non-normally distributed, the range or interquartile range may be used as a measure of variation.

2.4.2 Direct parameters

Recording data at the batch level requires batches to be individually identified. This is accomplished by entering the date a batch is opened in addition to assigning a batch-specific identification number. A batch is closed after the last pig has been sold. In continuous flow system, an identification number is assigned to the continuous flow location. Since a continuous flow location has no start or endpoint, this location is constantly active.

<u>Pig movements</u>

Accurate records of pig movements are required for calculations of batch averages such as average days to market and average daily feed intake. Batch averages represent the average performance of the entire batch or a subset of animals (e.g. only market pigs) over a specific period of interest, such as from weaning to market. Since the pig inventory of a batch changes over time, the cumulative number of pig days is used to track these changes. The cumulative number of pig days is the sum of the number of days each pig was in a batch during the period of interest. Errors in the cumulative number of pig days occur if pig movements are not tracked accurately.

Types of pig movements include batch entries, transfers to other batches, sales, and deaths. Minimum data requirements would be the type of movement, date of movement, and the number of moved pigs. Furthermore, it is beneficial to track the source of the pigs if pigs can enter a batch from a number of sources.

Tracking changes in the portion of pigs from different source populations allows adjusting for possible confounding effects when interpreting production data. The weight and, in case of batch entries, the age of moved pigs provide useful additional information for the interpretation of data.

An indicator of inaccurate recording of pig movements is the number of unaccounted pigs. Unaccounted pigs occur if the observed pig inventory does not match the recorded pig inventory after adjusting for recorded move-in and move-out events. Unaccounted pigs may occur if (1) entry numbers are inaccurate, (2) deaths or transfers are not recorded, (3) pigs escaped or stolen, or (4) sales numbers are inaccurate. Unless stock counts are taken throughout production, unaccounted pigs are only identified after a batch has been closed. Such inaccuracies may cause considerable bias in the calculation of batch averages as it is not normally known at what point in time misrecording or miscounting occurred.

Vaillancourt *et al.* (1992) evaluated the internal consistency of pre-weaning piglet numbers in litters during the suckling period. Whilst unaccounted piglets occurred in less than 15% of litters in 71% of 109 herds, the farm with the worst data quality had unaccounted pigs in 77% of litters. Litters with surplus recorded piglets occurred more frequently (8.0%) than litters with missing recorded piglets (4.7%). This suggests that errors occur more commonly in the tracking of pig movements including cross fostering and deaths than in the recording of the initial pig inventory (litter size at farrowing). To the author's knowledge, no studies exist investigating the prevalence of unaccounted pigs in growing batches. The considerably larger number of pigs in growing batches compared to the size of litters may be associated with a greater risk to make mistakes when recording the pig inventory and pig movements.

<u>Age</u>

The age of pigs, at which events occur, is of particular interest since production measures are known to change with age. Therefore, age needs to be considered as a confounding effect when comparing performance parameters such as weight, feed intake, and feed efficiency between groups of pigs. Furthermore, age at market may be used as an indicator of growth performance if pigs are marketed at similar weights. Additionally, the age at which pigs died may have diagnostic value in determining potential causes of mortality. Information about the variation in weaning age is very valuable as it influences weight variation of pigs in a batch.

Calculation of pig ages requires knowledge of the farrowing date, usually defined by the week of farrowing. More accurately, the average age of pigs should be derived from actual farrowing dates. If pigs are derived from different farrowing weeks, pig age identification may be accomplished with simple ear notching or tattooing. If the week of farrowing is unknown, days post-weaning can be used as an alternative measure to pig age. However, comparisons of wean-to-market performance between batches without an estimate of weaning age may be biased due to unknown differences in entry age.

Pig weights

The recording of live weight is probably the most common on-farm practice to assess pig performance. First, pig weights are used on their own, for instance to determine the optimum time of marketing the pig. Secondly, pig weights are necessary when calculating performance parameters such as feed efficiency and growth rate. Hence, it is important to understand sources of errors in weight measurements, and implement methods to reduce these errors.

The validity of recorded live weights depends on the extent to which apparent changes in live weight represent true changes in the weight of the carcass in relation to fluctuations of gut fill (Lawrence, 2002). Gut fill represents the difference between empty body weight and live body weight (Lewis and Southern, 2000), which comprises the weight of contents from the stomach, small and large intestine. Reported estimates of gut fill in pigs vary between 2% and 10% of live body weight (Stranks et al., 1988; Lawrence, 2002; Kyriazakis and Whittemore, 2006). The level of gut fill depends on several factors such as live weight, feeding level, diet characteristics, and time off-feed (Lewis and Southern, 2000). Two methods have been applied to reduce variability in gut fill that is standardization of weighing time and short-term feed withdrawal prior to weight measurement (Lawrence, 2002; Scanes, 2003). However, to the author's knowledge, no research exists clearly investigating the effect of these factors on the accuracy of live weight measurements.

At marketing, carcass weight is routinely assessed by the meat processing company when determining the carcass value. Carcass weight is measured after removal of intestinal contents, organs, blood, and offal. Carcass weight may be used on its own to assess to what extent the target weight range has been met. Carcass weight may also be used in combination with live weight measurements to determine the growth rate to slaughter. Lawrence (2002) addressed two sources of errors in the recording of carcass weight. First, the carcass shrinks for about 24 hours after slaughter in the chilling room, resulting in variable losses of carcass weight by up to 20 grams per kilo of carcass weight. Therefore, time after slaughter, at which carcass weight is recorded, needs to be standardized. Secondly, carcass weight depends on the definition of saleable carcass, particularly in relation to fat trimming. Hence, it is important to consider confounding effects of the abattoir when comparing carcass growth rate between batches. Another problem associated with routinely collected carcass weights is that these records generally do not allow distinguishing between pigs from different batches. Assigning mean carcass weight of a marketing batch to different batches, from which pigs were sold, introduces error in batch records.

Feed consumption

The amount of feed consumed by a group of animals needs to be measured to calculate average daily feed intake and feed efficiency. Measuring the amount of feed used may be difficult on commercial farms. The easiest method is to record changes in the feed inventory of silos, thus recording the feed inventory at the beginning of the period, the weight of feed entering the inventory during the period, and the weight in the inventory at the end of the period. However, silos generally supply several batches of pigs, so that it is hard to relate these records with batch records. On a batch or pen basis, feed consumption may be measured automatically, for instance by computerized liquid feeding systems, or manually. Automatic feeding stations, which continuously record feed intake of individual pigs, are not routinely used on commercial pig farms yet.

A common error in feed intake measurements is feed wastage. A general estimate of feed wastage is 5% of feed usage (Nyachoti et al., 2004). However, feed wastage can be highly variable between farms (Schinckel and deLange, 1996; Porkma$ter, 1997). For instance, measurements of feed wastage ranged from 1% to 25% in the study of Baxter (1991). Various factors influence feed wastage including feeder type, feeding method, and feeder space. For instance, trough feeding was found to increase feed wastage, whereas feeders with head barriers reduced feed wastage (Baxter, 1991). Hence, measuring and controlling feed wastage is important to obtain true estimates of feed intake and to reduce feed cost.

Back fat depth

Back fat depth is a useful indicator of the pig's lean tissue content (Hulsegge et al., 2000). Knowledge about lean tissue growth is important since it is the main determinant of production efficiency (Kyriazakis and Whittemore, 2006), carcass value (New Zealand Pork Industry Board, 2004), and nutrient requirements (Van Heugten, 2000). In New Zealand, financial penalties occur if back fat exceeds 12 mm. An optical electronic probe is used to measure back fat in pig carcasses, whereas ultrasound measurements are used to assess back fat depth in live animals. Measurements from both these methods (optical electronic probe versus ultrasound) were shown to be highly correlated (Chiba, 1995). See (1998) demonstrated that both the operator and ultrasound machine used may introduce bias in ultrasound back fat measurements.

2.4.3 Indirect parameters

Calculations of indirect parameters are based on more than one parameter. This has the advantage that a combination of parameters can be monitored effectively. However, a change in indirect parameters could be caused by a change in any of the raw parameters, thereby complicating problem detection. Furthermore, combining two parameters introduces errors from both individual parameters. The following section addresses the most commonly used outputs when monitoring the growing pig herd that is growth rate, average daily feed intake, feed efficiency, and mortality rate.

Growth rate

Growth rate is the total weight gain of a group over a defined period divided by the cumulative number of pig days within this period. If the starting point for growth rate calculation is the date of birth, birth weight should be subtracted from the final live weight to obtain weight gain. A common estimate for birth weight is 1.5 kg if real data are not available (Schinckel and deLange, 1996). The term carcass weight gain or carcass growth rate is used to indicate that the end weight was measured as carcass weight. Calculated growth rates may vary depending on whether it is adjusted for weights of dead and sick pigs (Dial and Rademacher, 2005). Therefore, it is beneficial to monitor growth rates both adjusted and unadjusted for losses throughout production.

Average daily feed intake

Average daily feed intake is an important performance parameter. First, feed intake records allow determining nutrient requirements. Secondly, feed intake is strongly related with growth performance. Thirdly, changes in feed intake patterns may be used as an early indicator of adverse circumstances such as disease. Average daily feed intake is determined by dividing the total amount of feed consumed over a specified period by the cumulative number of pig days during this period. Hence, inaccurate recording of feed usage and animal movements may introduce errors in average daily feed intake.

Feed efficiency

Feed efficiency is an important indicator of farm profitability. Feed efficiency is calculated by dividing total weight gain by the total amount of feed delivered. Another commonly used measure of feed efficiency is feed conversion ratio, which is simply the reciprocal term of feed efficiency. Values of feed efficiency may vary considerably between grower/finisher units. For instance, a national survey of commercial US pig farms (Losinger, 1998) aimed to assess live weight feed conversion ratio during the grower/finisher phase. Estimates derived from 212 farms ranged from 2.18 to 5.91 kg/kg with a mean of 3.28 kg/kg. This indicates that many farms may have opportunity to reduce feed conversion ratio, thus lowering feed cost. However, assessing feed efficiency may represent a challenge for producers, as it requires accurate tracking of feed consumption and weight gain. In the survey by Losinger (1998), 40.6% of the 212 farms indicated that values for feed consumption were based on estimates, which suggests that feed consumption is not routinely monitored on commercial farms. Furthermore, obtaining accurate estimates of feed efficiency requires that the weight of any pigs entering and leaving the group at any point in time is known, including deaths and sick pigs, which may be a tedious task.

Mortality and morbidity rate

Mortality and morbidity rate are useful in determining financial losses and identifying production problems. Monitoring the production stage, at which mortality/morbidity occurs, and likely causes for these losses may be helpful in diagnosing the cause of mortalities (Deen and Wattanaphansak, 2002a). The highest mortality rates generally occur in the first four weeks post-weaning and in the late finisher phase (Morrison et al., 2001). Economically, late mortality imposes a greater cost to the producer than early mortality. Pneumonia and gastric ulcers were identified as the two most common reasons for late finisher mortality (Straw et al., 1983; Morrison et al., 2001). Errors in mortality rate may arise if the beginning pig inventory or deaths are not recorded accurately. Hence, unaccounted pigs at the closure of the batch may be used as in indicator of errors in mortality rate.

2.5 Sources of errors and bias

It is important to understand the source and magnitude of errors and methods to reduce these errors in order to draw appropriate conclusions from collected data. Error, also referred to as uncertainty, may be defined as the difference between the true value and the observed value (Drosg, 2007). Errors may arise from data collection, data recording, and computation of results (Elwood, 1998). Furthermore, biological processes are dynamic and vary over time due to factors such as growth, diurnal and seasonal variation, which may cause within-subject variability.

Errors may lead to lack of precision (random error) or lack of validity (systematic error) (Delgado-Rodriguez and Llorca, 2004). Random error is defined as error that occurs by chance. Random error adds ‘noise’ to the data, thus making interpretation of data more difficult and obscuring underlying trends. Furthermore, when assessing differences between groups, random error causes the observed association being closer to zero. Therefore, random error increases the chance of the null hypothesis being rejected, when, in fact, it is true. One characteristic of random error is that it can be decreased by increasing sample size.

Systematic error or bias occurs if measurements systematically deviate from the truth. Hence, systematic errors produce a lack of validity (Noordhuizen et al., 2001), because they lead to distorted results and thus, possibly, misleading conclusions (Woodward, 2004). Bias may be classified by the direction of change they produce in a parameter. Toward the null bias produces estimates closer to the null value, whereas away from the null bias yields higher estimates than the true ones (Delgado-Rodriguez and Llorca, 2004).

Systematic error (bias) represents a more serious problem than random error and should be minimized as much as possible (Woodward, 2004). Sources of bias need to be minimized during the design and the performance of measurements. A common classification of types of bias is information bias, selection bias, and bias due to confounding (Dohoo et al., 2003; Delgado-Rodriguez and Llorca, 2004). Other types of bias exist and have been summarized by Delgado-Rodriguez and Llorca (2004).

2.5.1 Information bias

Information bias occurs during data collection and represents a type of measurement error. Measurement error is defined as the deviation of the result of measurement from the true value of the measurable quantity (Rabinovich, 2005). Two common sources of measurement bias are the measuring instrument and the operator of the instrument. For instance, See (1998) evaluated the effect of technician and type of ultrasound machine on measurement error in ultrasonic measures of back fat and longissimus muscle depth. Twenty-seven market pigs were measured by three different technicians using five different amplitude-mode (A-mode) ultrasound machines. Subsequently, measurements were taken using a brightness-mode (B-mode) machine as the gold standard. A general linear model was used to test the effect of machine, technician, and pig on the absolute difference between A- and B-mode measurements. The analysis found that both the machine type and technician were sources of bias. These results demonstrate the importance of assessing the accuracy of measurement instruments and operator.

2.5.2 Selection bias

Selection bias refers to the error introduced when the study population does not represent the target population (Delgado-Rodriguez and Llorca, 2004). Selection bias is a major problem as monitoring the grower herd commonly involves measuring a sample of pigs to draw inference s on the performance of the entire batch.

Measuring only a subset of animals produces sampling error. Sampling error is defined as the difference between the true value of the parameter in the study population and the value obtained from a sample (Henry, 1990). Sampling error includes sampling variation (random error) and sampling bias. Sampling bias refers to the error introduced when the study population does not represent the target population (Delgado-Rodriguez and Llorca, 2004). The level of sampling variation and sampling bias is dependent on the method used to select a sample.

Samples can be selected using either probability sampling or non-probability sampling. Probability sampling, also referred to as random sampling, assumes that every element in the population has a known non-zero probability of being selected (Dohoo et al., 2003). If every element has an equal chance of being selected, it is called a simple random sample. Other types of probability sampling are systematic random sampling, stratified random sampling, and cluster sampling. The reader is referred to textbooks for a detailed description of these probability sampling techniques (Lohr, 1999; Thompson, 2002; Dohoo et al., 2003).

Probability samples eliminate sampling bias since all units have an equal chance of being selected. It is possible to estimate the magnitude of the random sampling error using the formula for the respective random sampling strategy, which can be derived from textbooks (Lohr, 1999; Thompson, 2002). For simple random samples, the standard error of the sample ($se = \sigma / \sqrt{n}$) is used as an approximation for the sampling error. This implies that the sampling error reduces when sample size increases.

Non-probability sampling includes judgement sampling, convenience sampling, and purposive sampling. A judgement sample is chosen because it is thought to be representative of the target population. A convenience sample is chosen because it is easy to obtain. For instance, producers may choose the pens that are located closest to the scale. A purposive sample is selected because its elements possess certain attributes (e.g. certain breed).

In contrast to random sampling, non-probability sampling is prone to introduce sampling bias. Therefore, sampling errors cannot be extrapolated to provide estimates on the population. Furthermore, the size of the sampling errors cannot be estimated a priori and cannot be reduced with an increase in sample size.

2.5.3 Bias due to confounding

Bias due to confounding occurs when variability in measurements is caused by variability in unmeasured preceding variables. Experimental studies allow controlling for potential confounders. In contrast, observational data are prone to variation due to uncontrolled confounders. Typically, the confounding in observational studies is adjusted for at the analytical stage using stratification or multivariate analysis (Thrusfield, 2005). However, application of these analytical methods to control for confounding depends on the collection of data relating to these confounders. Since unmeasured confounders are likely to be present in observational measurements, data need to be interpreted after considering the potential effect of unmeasured confounders.

2.6 Conclusion

This review has provided an overview of the monitoring process in the growing pig herd and sources of errors in pig weight records. It addressed the application of performance monitoring in the growing herd to optimize profit. The review also addressed what performance data are typically collected in the growing herd.

Pig weights have been identified as important performance parameters as they are used for decision-making on their own or after calculation of indirect parameters such as growth rate and feed efficiency. Therefore, improving accuracy of pig weight measurements affects the effectiveness of the monitoring system. To the author's knowledge, there is a lack of studies clearly investigating sources of errors in manually measured pig weights. Hence, three studies were designed to investigate sources and magnitude of errors in pig weight measurements.

Chapter 3 Description of the study farm

Data analysed in subsequent chapters were derived from a commercial pig farm located in the lower half of the North Island, New Zealand. The farm is a 270-sow farrow-to-finish piggery. The farm sourced Large White × Landrace breeding stock from a breeding company. Piglets were farrowed in batches, and male piglets were not castrated.

3.1.1 Pig flow

The farm weaned piglets at approximately four weeks of age and managed them as batches using a three-stage production system: (i) weaner, (ii) grower, and (iii) finisher stage. At weaning, the majority of weaned piglets entered the weaner rooms, whilst the lightest weaned piglets were moved to a special rearing location. Pigs that went directly to the weaner rooms were managed as weaner pigs for 40 days, grower pigs for 38 days, and finisher pigs for approximately four weeks until marketing. Pigs from the special rearing location re-entered the batch production system at either the weaner or the grower stage by joining a group of pigs that was weaned one to two weeks later. Consequently, a single batch may include pigs of different ages. Batches were sold using a split marketing system - that is a single batch was sold in several lots. The decision on when to market an individual pig was based on pre-market live weight measurements taken within two days prior to marketing.

3.1.2 Housing facilities

Housing facilities provided space for the introduction of 110 to 120 weaned pigs per week. Weaner and grower batches were housed in one single shed. In contrast, finisher batches were placed in one of four finisher sheds (Figure 3.1). Shed characteristics are described in Table 3.1. The housing capacity of the weaner shed (120 pigs per batch) was greater than that of the grower and finisher sheds (100 to 117 pigs per batch). If there were surplus pigs at transfer from the weaner to the grower shed, they were housed in an alternative shed (shed E). Pigs transferred to shed E remained in this shed until marketing. Typically, pens with the heaviest pigs of the batch were moved to shed E to allow early marketing of these animals due to space restrictions in this shed.

Pigs were housed in pens as mixed-gender groups. It was routine farm management to allocate pigs to pens as follows: at weaning, pigs were sized to match pen mates. Since the number of pens increased at subsequent production stages, the smallest pigs from each pen were mixed to create new pens. The remaining pigs were moved to pens of the next production stage as one group.

3.1.3 Feeding

The farm fed four diets throughout the growing period (Table 3.2). Diets were home-mixed grain-based diets. Wheat was a common component of weaner diets, whereas barley was the predominant grain source in grower and finisher diets. Weaner and grower pigs were fed ad libitum from one double-sided wet-dry feeder. Finisher pigs housed in shed E were fed ad libitum from one double-sided wet-dry feeder. Finisher pigs housed in sheds A to D were fed four times a day via a computerized liquid feeding system. The feeding times for the computerized liquid feeding system were 0830, 1015, 1430, and 2000. The feed allowance for pigs fed via a computerized liquid feeding system was approximately 85% of ad libitum feed intake. All pigs had continuous access to water.

3.1.4 Collection of weight records

The growing pig herd was operated by three staff members who had been working on the farm for at least two years prior to when data were collected. No changes in staff occurred throughout the study period. The producer and/or staff members routinely collected weight records at various stages of production. All grower pens were weighed three days after pigs were transferred from the weaner to the grower shed. Weights for finisher pens were recorded at the time of transfer from the grower to the finisher shed. For market selection, all pigs were weighed individually. Weight measurements were taken in the late morning. The scales were calibrated weekly and their resolution was 0.5 kg.

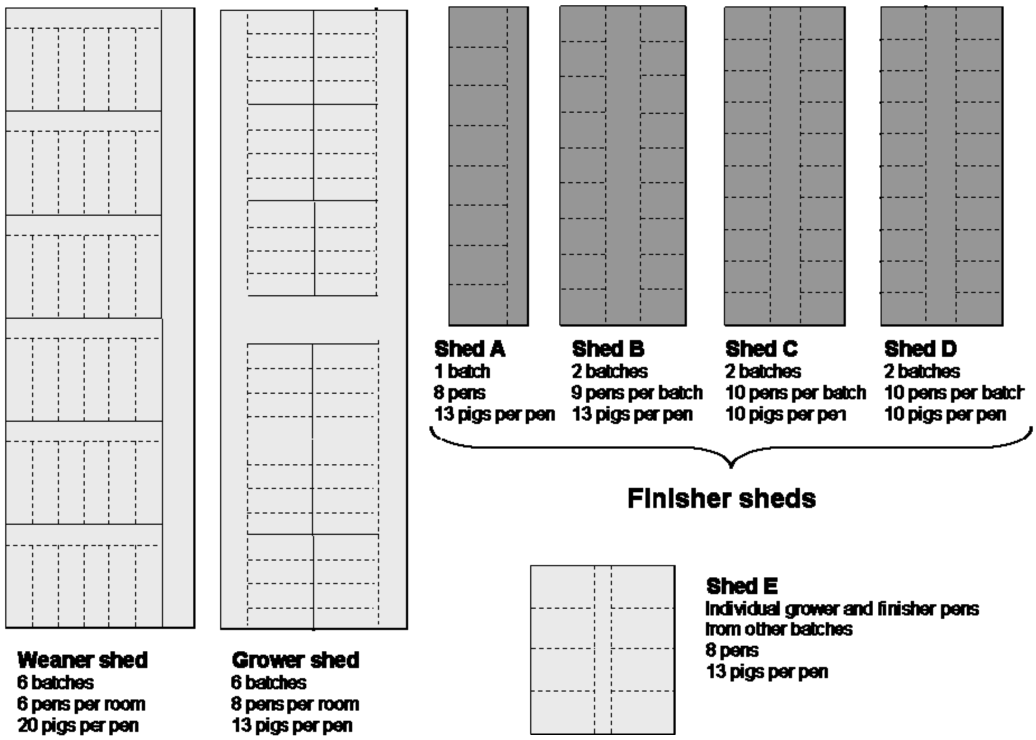

Figure 3.1. Schematic plan of growing herd facilities on a commercial pig farm located in the North Island, New Zealand. Pigs were fed ad libitum (light shaded sheds) or via a computerized liquid feeding system (dark shaded sheds). Dashed lines indicate open air space. Shed and pen dimensions as well as relative locations between sheds are not drawn to scale.

Table 3.1. Features of growing herd housing facilities on the study farm.

Features	Weaner shed [a]	Grower shed [a]	Finisher sheds [a]				Grower / finisher
			Shed A	Shed B	Shed C	Shed D	Shed E
Number of batches per shed	6	6	1	2	2	2	NA [b]
Number of pens per batch	6	8	8	9	10	10	8
Number of pigs per pen	20	13	13	13	10	10	13
Lighting	Artificial	Natural	Natural	Natural	Natural	Natural	Natural
Flooring	Partly slatted	Fully slatted	Concrete	Partly slatted	Concrete	Concrete	Partly slatted
Ventilation	Auto control	Auto control + natural	Man control	Natural	Natural	Natural	Natural
Heat source	Heat lamps	None	None	None	None	None	None
Separation of airspace between batches	Yes	Yes	Yes	No	No	No	No
Trough space per pen	1 double-sided feeder	1 double-sided feeder	2.4 m	2.4 – 3.6 m	3.6 m	3.6 m	1 double-sided feeder
Feeding system	Wet-dry [c]	Wet-dry [c]	Liquid	Liquid	Liquid	Liquid	Wet-dry [c]
Access to feed	Ad libitum	Ad libitum	Computer-controlled	Computer-controlled	Computer-controlled	Computer-controlled	Ad libitum

[a] Pigs entered the weaner shed at 28 days, the grower shed at 68 days, and the finisher shed at 106 days of age.
[b] NA: Not applicable.
[c] Wet-dry feeding: Feeders combined with drinkers so that pigs can mix feed with water.

Table 3.2. Nutritional composition of diets fed to growing pigs on the study farm.

Production stage	Start age (days)	Digestible energy (MJ / kg)	Crude protein (%)	Lysine (%)
Weaner	28	15.6	21.0	1.50
	42	14.4	23.0	1.22
Grower	68	13.5	20.0	1.01
Finisher	106	13.0	16.0	0.82

Chapter 4 Diurnal fluctuations in live weight as a potential cause for variability in weight records

Abstract

AIM: To determine the effect of time of day on live weight of finisher pigs fed via either a computerized liquid feeding system or ad libitum.

METHODS: The experiment used finisher pigs fed either ad libitum (AL-group) or via a computerized liquid feeding system (CL-group). Pigs were housed on a commercial piggery in the North Island, New Zealand. The feeding times for the CL-group were 0830, 1015, 1430, and 2000. Two replicates were conducted in September of subsequent years. In each replicate, pigs were weighed individually at 0700, 1030, 1400, and 1730 over a four-day period. Mean pig weight and coefficient of variation in pig weight (CV) were plotted over time. For each feeding system, a repeated measures mixed model was used to investigate the effect of time of day on pig weight whilst accounting for day, pen, gender, and start weight.

RESULTS: The experiment consisted of 81 pigs, of which 37 pigs were in the AL-group (15 pigs in 2003 and 22 pigs in 2004) and 44 pigs in the CL-group (19 pigs in 2003 and 25 pigs in 2004). Mean weight changed with time of day. The change in mean pig weight appeared to be consistent within replicate and between replicates of the same feeding system. Diurnal fluctuations in mean weight of pigs in the CL-group were consistent with time of feed deliveries, whereas mean weight of pigs in the AL-group increased steadily throughout the day and dropped over night. In contrast, diurnal changes in CV were small and did not show a clear pattern over time. The factors day, time of day, and start weight showed significant associations with live weight in multivariate models of both groups, whilst pen was only significant for the AL-group. An interaction between time of day and day was significant for both groups.

CONCLUSION: Weight varied within a day, and these variations appeared to be associated with feed intake patterns. Therefore, results provide an indirect indication that variability in gut fill represents a source of error in live weight measurements. The results showed that diurnal fluctuation in weight due to variation in gut fill can be reduced by keeping weighing time as well as feeding time in a CL-situation constant. However, standardization of weighing time

appears insufficient to eliminate variability in pig weights due to biological factors such as gut fill, particularly if pigs are fed ad libitum.

4.1 Introduction

Pig weight measurements represent key performance parameters when monitoring growing herd performance. First, pig weights may assist producers in marketing decisions. Secondly, pig weights are necessary when calculating performance parameters such as feed efficiency and growth rate. Thirdly, as animal attributes, pig weights indicate the animal's response to its environment (Dohoo et al., 2003). Therefore, weight records may allow producers to identify environmental problems and assess the effect of management changes. The ability to make effective decisions from recorded pig weights is dependent on the accuracy of the weight measurements. Hence, factors need to be investigated that affect the accuracy of weight records on commercial farms.

The most important indirect parameter calculated from pig weights is growth rate. Growth is defined as the increase in size of the tissues and organs that occurs from conception through maturity (Grant and Helferich, 1991). Hence, gut fill does not contribute any information regarding the growth of the animal. Gut fill was estimated to comprise about 5% of live weight (Kyriazakis and Whittemore, 2006). However, this estimate may only be applicable under restricted feeding, and if pigs are weighed before feeding (Stranks et al., 1988). Stranks proposed gut fill levels of approximately 10% if pigs are fed ad libitum or weighed shortly after feeding. Based on the magnitude of these estimates, it is hypothesized that fluctuations in gut fill due to feed and water intake as well as defecation may present a source of variability in weight records.

Standardization of weighing time is a traditional method to reduce weight variability due to food and water intake (Lawrence, 2002; Scanes, 2003). To the author's knowledge, a precise estimation and validation of the effect of time of day on pig weight measurements has not been published. Hence, the objective of this chapter was to determine the effect of time of day on live weight of finisher pigs fed via either a computerized liquid feeding system or ad libitum. This information was used to evaluate whether standardizing weighing time could reduce error in pig weights due to variation in biological factors such as gut fill.

4.2 Materials and methods

4.2.1 Farm management

The experiment was conducted using finisher pigs housed on a commercial New Zealand piggery. Detailed description of farm management can be found in Chapter 3 of this thesis. Briefly, the studied farm managed weaned pigs in batches using a three-stage production system (weaner, grower, and finisher stage). Four sheds (sheds A to D) with different housing capacity were used to house finisher pigs. A separate shed (shed E) was used to house surplus pens of pigs at the grower and finisher stage. Finisher pigs housed in sheds A to D were fed four times a day via a computerized liquid feeding system at 0830, 1015, 1430, and 2000. Pigs housed in shed E received feed ad libitum from one double-sided wet-dry feeder. All pigs had continuous access to water.

4.2.2 Study design

The study included finisher pigs that were fed ad libitum (AL-group) or via a computerized liquid feeding system (CL-group). For each group, two replicates were conducted in September of subsequent years (2003 and 2004). Each replicate included two pens per feeding system. The pens were convenience sampled from batches between 16 and 20 weeks of age. Pigs were individually identified and weighed four times a day over a four-day period, resulting in 16 measurements per pig. Pigs were weighed daily at 0700, 1030, 1400, and 1730. Pigs were moved out of their pen as a group and held until they were weighed. It took 10 to 15 minutes to weigh all the pigs from a single pen. Pens were always weighed in the same order starting with pens of the CL-group, whilst the weighing order of individual pigs was random. Scales were calibrated before each weighing time and their resolution was 0.1 kg.

4.2.3 Statistical analysis

Mean pig weight per pen at transfer to the finisher shed was derived from routinely collected farm data by dividing total pen weight by the number of pigs in each pen. Normality of individual pig weights at time 0 was assessed by visual inspection of frequency histograms. Growth rates were calculated for each pig using 0700 weights measured on days 1 and 4. Descriptive results of number of pens and pigs, age, pig weights, and four-day growth rate were produced. Non–normally distributed variables were summarised using median and percentiles. Normally distributed variables were summarised using mean and 95% confidence interval of the mean. For each feeding system, a two-sample *t*-test was used to determine if there were significant weight differences between replicates at time 0. The coefficient of variation in live weight (CV) was used as a comparative measure of variation over time. Mean live weight and CV stratified by year of replicate were plotted over time. All descriptive results were presented stratified by feeding system and year of replicate.

A multivariate analysis was conducted to determine factors affecting observed pig weights. Since the effect of feeding system was not of primary interest, separate models were created for each feeding system. The sequence of weight measurements within pig was specified as the temporal variable identifying repeated weight measurements (j = 1 to 16).

Weight measurements within an individual pig were assumed to be correlated in time. To account for this cluster effect, a repeated-measures mixed linear model was used, which is represented as:

$$Y_{ij} = X_i \beta + \varepsilon_{ij} ,$$

where Y_{ij} is the weight of animal i at measurement j, X_i is the fixed design matrix of animal i, β is a vector of unknown fixed effects, and ε_{ij} is the error vector.

Observations within the same subject (i = i') were allowed to be correlated and a pattern for their covariances, cov(Y_{ij}, $Y_{i'j'}$), was specified in the residual matrix (R matrix) (Brown and Prescott, 1999). Models were compared using the Akaike's information criterion (AIC) (Wolfinger, 1993). The model with a first order Autoregressive covariance term (AR(1)) produced the minimum AIC when compared with alternative covariance structures. Variance parameters in the R matrix (γ_R) were estimated using the Maximum Likelihood (ML) method. For measurements taken on different animals (i ≠ i'), cov(Y_{ij}, $Y_{i'j'}$) was 0, since their errors were assumed to be independent.

Fixed effects included in the model were day, time of day, pen, gender, and start weight. Explanatory variables were selected using backward selection based on P-values derived from the type III F-test. Pen was forced into the model as it was considered an important cluster variable. All biologically plausible two-way interactions were tested for significance using the likelihood ratio χ^2-test (McCullagh and Nelder, 1989). Interaction graphs were created for each significant interaction (Cobb, 1998). Model fit was assessed by visual inspection of residuals.

Statistical analyses were performed in SAS for Windows (Version 9.1) and graphics were produced in R for Windows (Version 2.3.1) or Microsoft Office Excel 2003. The level of significance was set at P = 0.05.

4.3 Results

4.3.1 Descriptive results

Table 4.1 presents descriptive statistics of pig numbers, ages, and pig weights stratified by feeding system and year of replicate. The 2003 replicate had six fewer pigs in the CL-group and seven fewer pigs in the AL-group than the 2004 replicate. In both years, pigs in the CL-group were two to three weeks older than pigs in the AL-group. Furthermore, pigs in the 2003 replicate were one week older than pigs of the same group in the 2004 replicate. The age difference between replicates of the CL-group was not associated with weight differences at study start ($P = 0.82$). In contrast, pigs in the AL-group were 7.9 kg (95% CI: 4.3 to 11.6 kg) heavier at study start in the 2003 replicate compared to the 2004 replicate ($P < 0.001$).

Figure 4.1 depicts the fluctuations in mean live weight for pigs in the CL-group, stratified by year of replicate. The pattern of change in mean weight seemed to correspond with time of feed deliveries. Figure 4.2 describes the changes in mean live weight during the experimental period for pigs in the AL-group, by year of replicate. In contrast to pigs in the CL-group, the mean weight of pigs in the AL-group increased steadily throughout the day and then declined over night.

Figure 4.3 and Figure 4.4 illustrate changes in variation in pig weights, which was expressed as coefficient of variation (CV). The graphs indicate that CV showed no clear pattern over time for either experimental group. The maximum range in CV on a single day was 0.4% for pigs in the CL-group and 0.8% for pigs in the AL-group.

4.3.2 Multivariate analysis

Table 4.2 illustrates the main effect model for factors affecting live weight of pigs in the CL-group. The factors day, time of day, and start weight showed significant associations with live weight. After accounting for confounders, pigs were 3.2 kg, 1.7 kg, and 2.2 kg heavier at 1030, 1400, and 1730, respectively, compared to

0700 weights. The effect of pen location on live weight was not significant (P = 0.10).

Table 4.3 presents the main effect model for factors affecting live weight of pigs in the AL-group. Day, time of day, start weight, and pen were significant main effects. The pens of the 2003 replicate were significantly heavier than the pens of the 2004 replicate. After accounting for confounders, pigs were 0.4 kg, 1.0 kg, and 2.2 kg heavier at 1030, 1400, and 1730, respectively, compared to 0700 weights.

Significance tests for interaction terms are presented in Table 4.4. The interaction between day and time of day was significant for both groups. The change in effect of time of day between days is graphically displayed in Figure 4.5 and Figure 4.7 for the CL- and AL-group, respectively. The effect of time of day varied between pens of the CL-group (Figure 4.6) For pigs in the AL-group, the effect of start weight on predicted weight differed between pens as illustrated in Figure 4.8.

Table 4.1. Number of pens and pigs, age, live weight, and growth rate for finisher pigs by feeding system and year of replicate.

Feeding system	Year	Number of		Age (weeks)	Mean live weight (95% CI [a]) (kg)		Median growth rate [b] (IQR) (g/d)
		Pens	Pigs		At entry to the finisher stage [c]	At study start	
Computerized liquid feeding							
	2003	2	19	19.5	64.4	82.3 (79.2 – 85.4)	800 (600 to 1000)
	2004	2	25	18.5	66.4	82.7 (80.8 – 84.6)	900 (750 to 1100)
	Total	**4**	**44**	**19.0**	**65.5**	**82.5 (80.9 – 84.1)**	**825 (700 to 1050)**
Ad libitum feeding							
	2003	2	15	17.0	73.0	82.1 (78.4 – 85.8)	650 (400 to 750)
	2004	2	22	16.0	70.9	74.7 (71.3 – 78.2)	450 (200 to 600)
	Total	**4**	**37**	**16.5**	**71.8**	**77.7 (75.0 – 80.4)**	**500 (300 to 700)**

[a] 95% confidence interval of the mean.
[b] Growth rates were calculated for each pig using weight measurements at 0700 on days 1 and 4.
[c] Pigs entered the finisher stage at 15 weeks of age; 95% confidence intervals could not be estimated, as individual pig weights were not available.

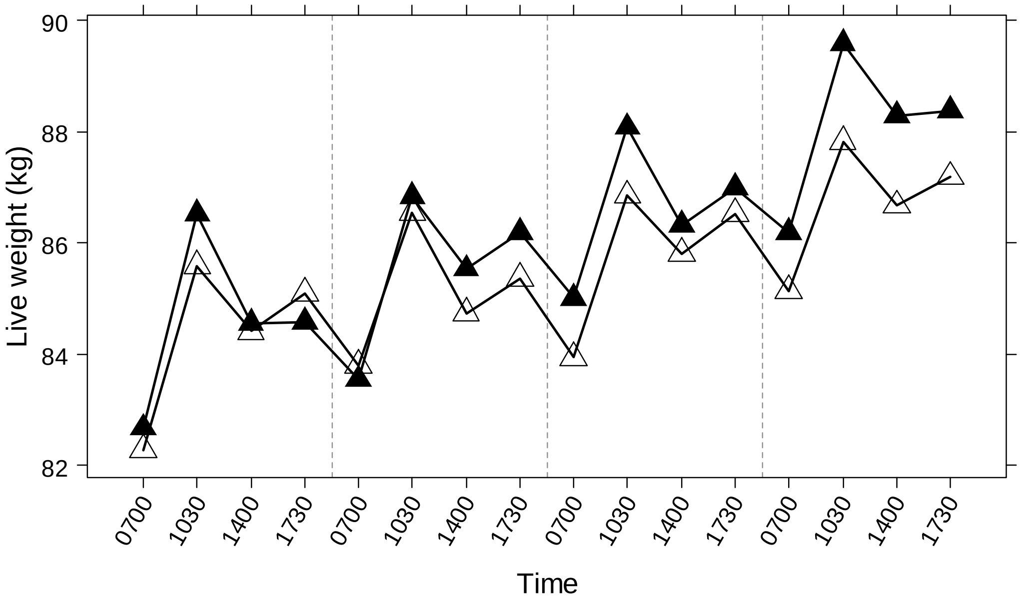

Figure 4.1. Changes in mean live weight of finisher pigs fed via a computerized liquid feeding system, for animals in 2003 (△, n = 19) and animals in 2004 (▲, n = 25). Dashed lines denote the different days. Feeding times were 0830, 1015, 1430, and 2000.

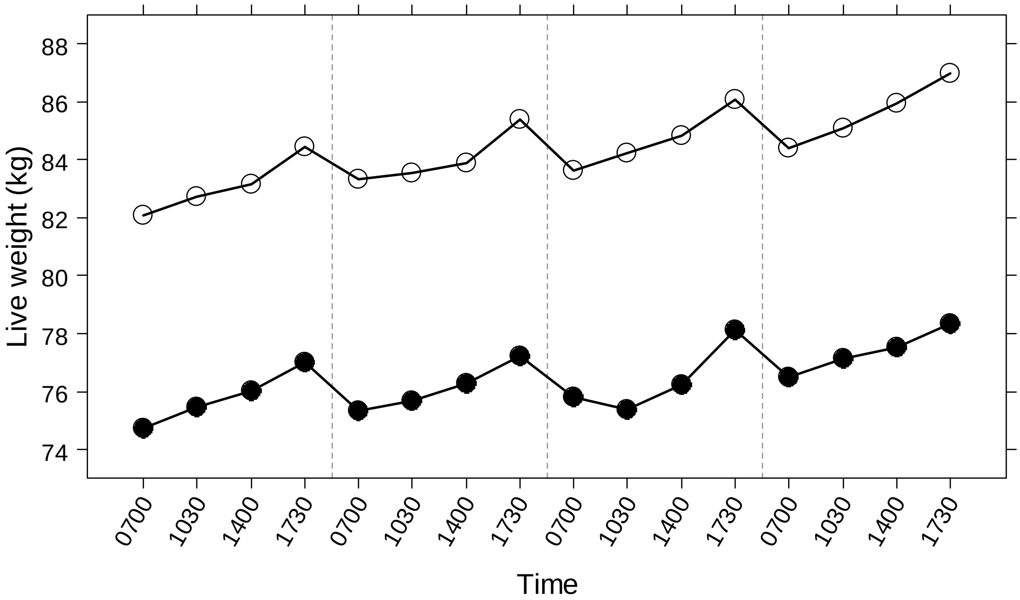

Figure 4.2. Changes in mean live weight of finisher pigs fed ad libitum, for animals in 2003 (○, n = 15) and animals in 2004 (●, n = 22). Dashed lines denote the different days.

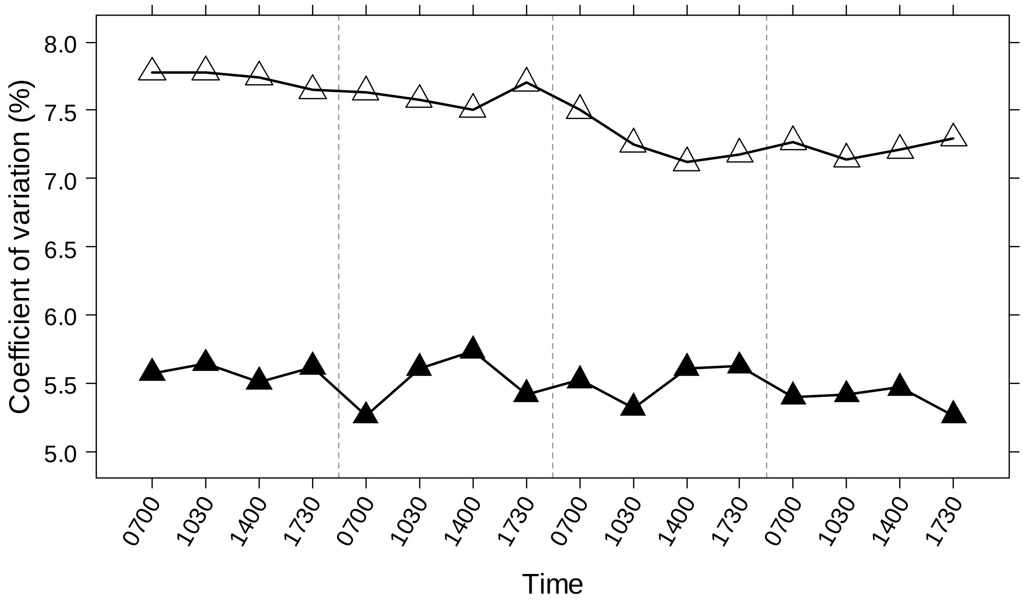

Figure 4.3. Changes in coefficient of variation in live weight of finisher pigs fed via a computerized liquid feeding system, for animals in 2003 (△, n = 19) and animals in 2004 (▲, n = 25). Dashed lines denote the different days. Feeding times were 0830, 1015, 1430, and 2000.

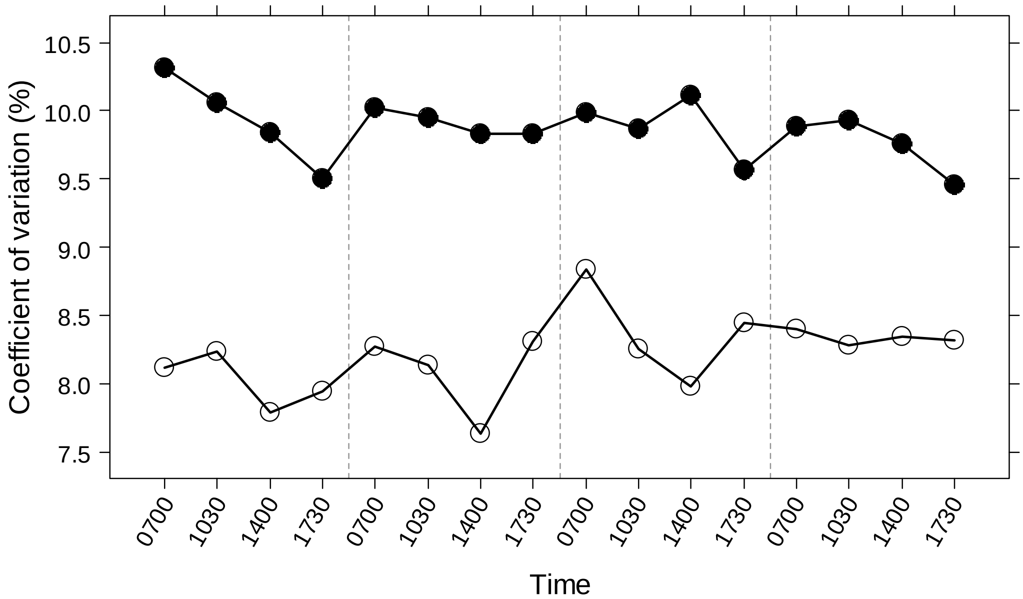

Figure 4.4. Changes in coefficient of variation in live weight of finisher pigs fed ad libitum, for animals in 2003 (○, n = 15) and animals in 2004 (●, n = 22). Dashed lines denote the different days.

Table 4.2. Mixed linear model for predicting live weight (304 measurements from 19 pigs in 2003; 400 measurements from 25 pigs in 2004) for finisher pigs fed via a computerized liquid feeding system that delivered feed at 0830, 1015, 1430, and 2000.

Effect type	Variable	Level	Beta	SE	P-value [a]	Variance component
Covariance						
	AR(1) [b]					0.72
	Residual					1.48
Fixed effects						
	Intercept		1.43	1.99	0.48	
	Day	1	REF [c]		<0.001	
		2	1.03	0.13		
		3	1.94	0.17		
		4	3.10	0.20		
	Time	0700	REF		<0.001	
		1030	3.19	0.06		
		1400	1.73	0.08		
		1730	2.20	0.08		
	Weight at time 0 (kg) [d]		0.98	0.02	<0.001	
	Pen	Pen 1, 2003 replicate	REF		0.10	
		Pen 2, 2003 replicate	-0.16	0.36		
		Pen 1, 2004 replicate	0.51	0.31		
		Pen 2, 2004 replicate	0.01	0.30		

-2 Log Likelihood test statistic 1786.4, 11 df, P < 0.001.
[a] P-value for the Type III F-statistic.
[b] AR(1) of the repeated measure of weight within pig.
[c] Reference category.
[d] Weight at time 0 is the pig weight at the first measurement.

Table 4.3. Mixed linear model for predicting live weight (240 measurements from 15 pigs in 2003; 352 measurements from 22 pigs in 2004) for finisher pigs fed ad libitum.

Effect type	Variable	Level	Beta	SE	P-value [a]	Variance component
Covariance						
	AR(1) [b]					0.68
	Residual					1.16
Fixed effects						
	Intercept		1.83	1.21	0.14	
	Day	1	REF [c]		<0.001	
		2	0.70	0.13		
		3	1.29	0.17		
		4	1.92	0.19		
	Time	0700	REF		<0.001	
		1030	0.40	0.07		
		1400	0.98	0.08		
		1730	2.19	0.08		
	Weight at time 0 (kg) [d]		0.98	0.01	<0.001	
	Pen	Pen 1, 2003 replicate	REF		0.04	
		Pen 2, 2003 replicate	0.53	0.28		
		Pen 1, 2004 replicate	-0.69	0.32		
		Pen 2, 2004 replicate	-0.25	0.27		

-2 Log Likelihood test statistic 1425.5; 11 df; $P < 0.001$.
[a] P-value for the Type III F-statistic.
[b] AR(1) of the repeated measure of weight within pig.
[c] Reference category.
[d] Weight at time 0 is the pig weight at the first measurement.

Table 4.4. Evaluation of all plausible two-way interactions for variables in a mixed linear model of live weight in finisher pigs fed via a computerized liquid feeding system (n = 44) and ad libitum (n = 37). Measurements on the same subject (pig) were modelled as a repeated effect using a first order autoregressive covariance structure.

Model	Computerized liquid feeding				Ad libitum feeding			
	-2ln L [a]	LRT [b]	Degrees of freedom	P-value [c]	-2ln L [a]	LRT [b]	Degrees of freedom	P-value [c]
Main effects	1786.4				1425.5			
Main effects + Day [d] × Time [e]	1763.6	22.8	9	0.01	1394.5	31.0	9	<0.001
Main effects + Wgt0 [f] × Time	1781.2	5.2	3	0.16	1421.8	3.7	3	0.30
Main effects + Pen [g] × Time	1736.6	49.8	9	<0.001	1413.9	11.6	9	0.24
Main effects + Pen × Wgt0	1782.5	3.9	3	0.27	1401.8	23.7	3	<0.001

[a] -2 Log Likelihood (smaller value indicates better model fit).
[b] Likelihood ratio test statistic computed as the difference between -2 Log Likelihood of the main effects model and the model including interaction terms.
[c] P-value based on a chi-square distribution.
[d] Pigs were weighed on each of four subsequent days.
[e] Each day, pigs were weighed starting at 0700, 1030, 1400, and 1730.
[f] Pig weight at the first measurement.
[g] Each feeding system included pigs from four different pens.

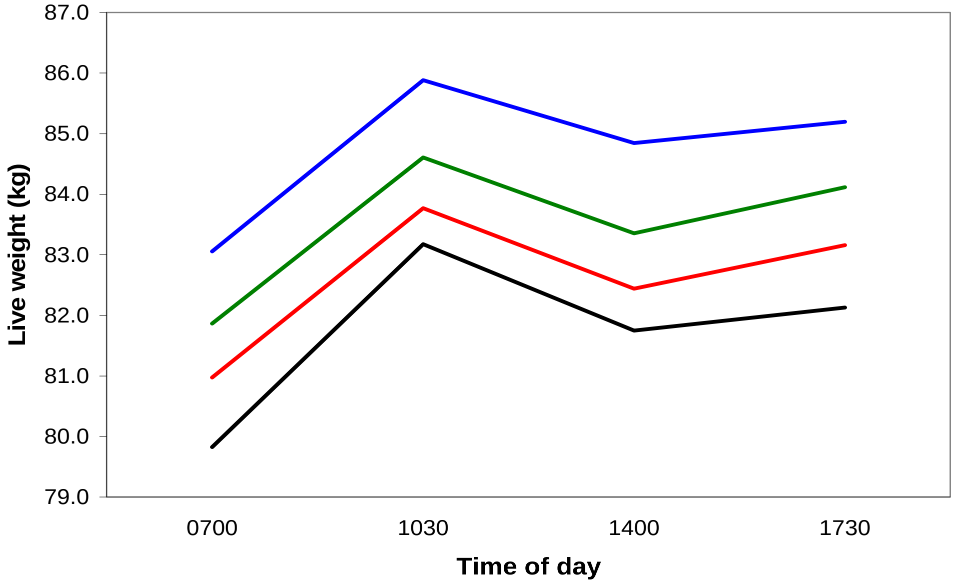

Figure 4.5. Interaction graphs showing the change in live weight of an 80-kg finisher pig fed via a computerized liquid feeding system at 16 combinations of time of day and day. Data from an experiment in which pigs were weighed four times a day over a four-day period. Black, red, green, and blue lines represent the first, second, third, and fourth day, respectively.

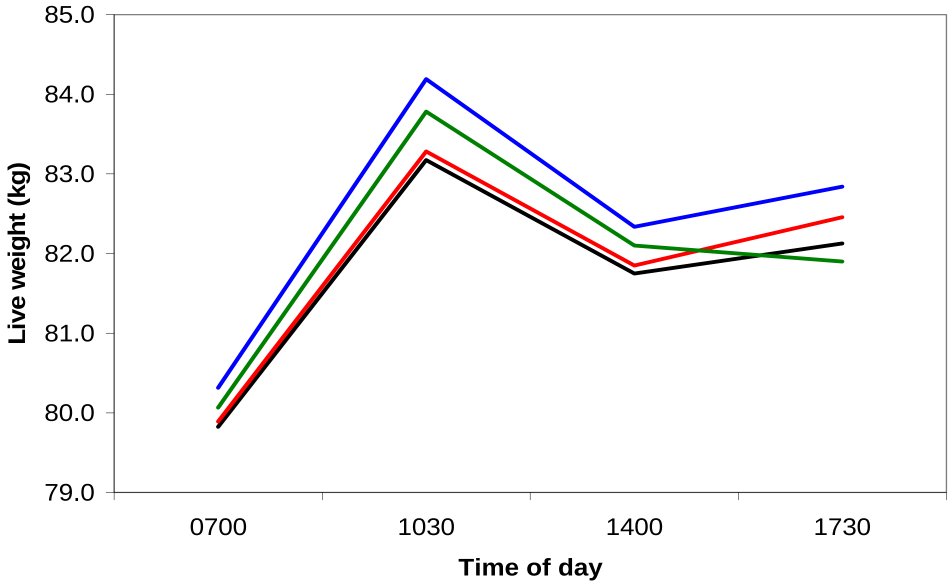

Figure 4.6. Interaction graphs showing the change in live weight of an 80-kg finisher pig fed via a computerized liquid feeding system at 16 combinations of time of day and pen. Data from an experiment, in which pigs were weighed four times a day over a four-day period. The experiment included two replicates and two pens per replicate. Black, red, green, and blue lines represent pen 1/2003, pen 2/2003, pen 1/2004, and pen 2/2004, respectively.

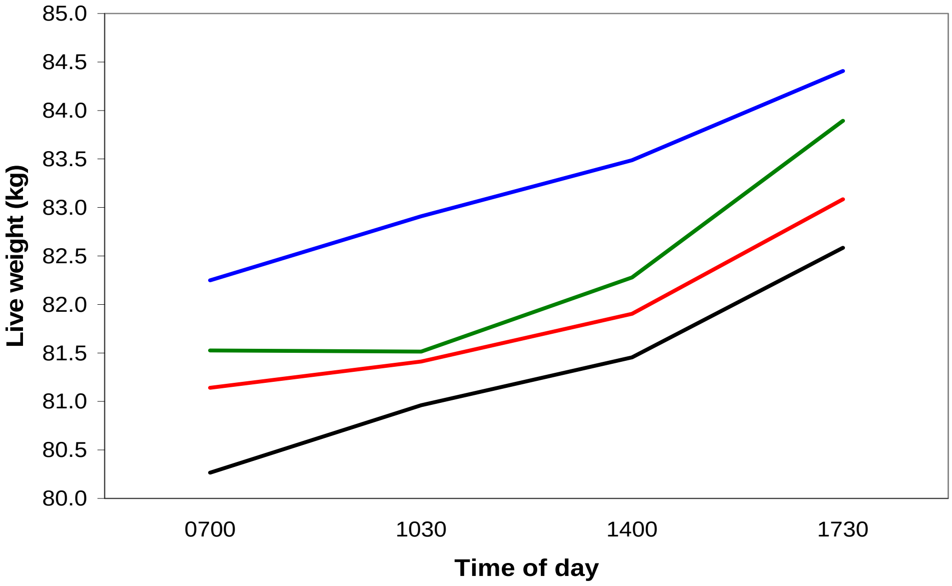

Figure 4.7. Interaction graphs showing the change in live weight of an 80-kg finisher pig fed ad libitum at 16 combinations of time of day and day. Data from an experiment, in which pigs were weighed four times a day over a four-day period. Black, red, green, and blue lines represent the first, second, third, and fourth day, respectively.

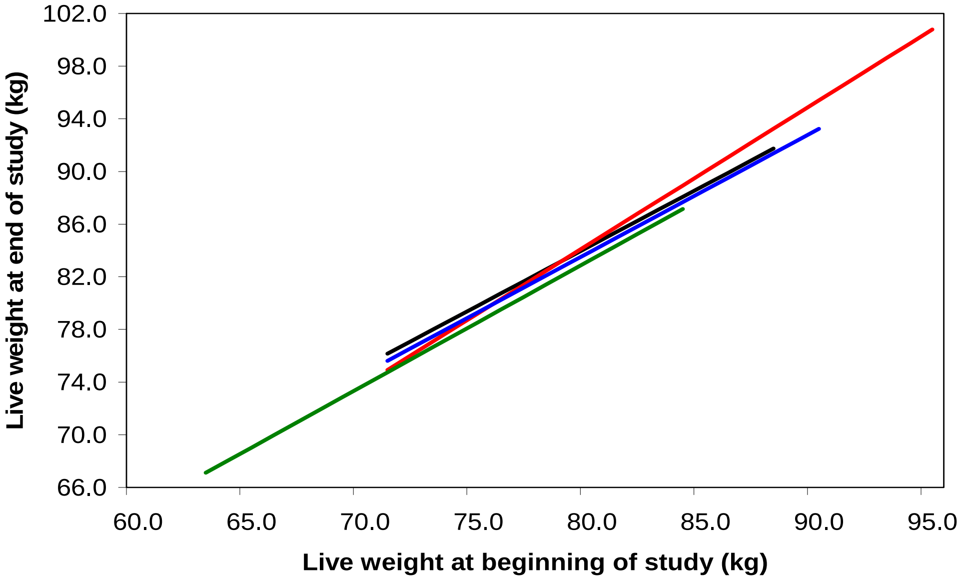

Figure 4.8. Interaction graphs showing the change in live weight of an 80-kg finisher pig fed ad libitum in response to weight at study start and pen location. Data from an experiment, in which pigs were weighed four times a day over a four-day period. The experiment included two replicates and two pens per replicate. Black, red, green, and blue lines represent pen 1/2003, pen 2/2003, pen 1/2004, and pen 2/2004, respectively.

4.4 Discussion

The two feeding systems investigated in this study are the most common feeding systems used to feed commercial finisher pigs (Kyriazakis and Whittemore, 2006). However, care should be taken when extrapolating the results of the study beyond the study population as data were derived from a convenience sample of eight finisher pens from one New Zealand pig farm. Convenience sampling rather than random sampling was used to select two pens per feeding system and replicate for two reasons. First, two pens were not considered a large enough sample size to represent a true random sample. Secondly, the number of eligible pens in shed E (AL-group) was limited because the shed only housed pens from those batches, for which batch size exceeded the housing capacity of routinely used grower and finisher sheds.

This chapter aimed to determine the effect of time of day on live weight of finisher pigs fed via either a computerized liquid feeding system or ad libitum. It is known that pigs show different feeding patterns depending on whether they are ration fed or have continuous access to feed (Botermans et al., 2000). Feed intake is the main determinant of gut fill, which in turn is likely to affect short-term live weight changes. Consequently, gut fill levels and thus live weight changes were expected to vary between feeding systems. Therefore, it was not of interest to assess the direct effect of feeding system on the magnitude of weight change, but rather to compare weight change patterns between feeding systems.

Care should also be taken when interpreting the results because the actual act of weighing pigs may have altered feeding behaviour and may therefore have affected live weight changes. Augspurger and Ellis (2002) investigated the impact that the act of weighing pigs has on feed intake using data from two separate experiments. In the first experiment, 60 finisher pigs were individually housed and weighed weekly for four weeks. In the second experiment, 48 grower/finisher pigs weighing between 40 and 120 kg were group housed and weighed every two weeks for a total of ten weeks. Multivariate repeated measures analysis found that weighing altered feeding behaviour including feeder occupation time per visit and number of feeder visits per day. This resulted in reduced feed intake on the day of weighing compared to adjacent days. The implications of these findings on the current study are unclear. However, weighing pigs manually may have biased the magnitude of weight changes, whereas the patterns of weight change were not expected to change.

The difference in observed four-day growth rates between pigs in the CL-group (825 g/d) and pigs in the AL-group (500 g/d) could be partly explained by pigs in the CL-group being two to three weeks older than pigs in the AL-group. However, the difference appears relatively large since transfer weights to the finisher shed suggest that pigs in the AL-group were heavy-for-age pigs. At transfer, pigs in the AL-group were 8.6 kg (2003 replicate) and 4.5 kg (2004 replicate) heavier than pigs in the CL-group. Several studies showed that heavy-for-age pigs tend to grow faster at subsequent production stages (Mahan, 1993; Wolter and Ellis, 2001; Dunshea et al., 2003). Four other studies were found that took longitudinal weight measurements in commercially housed finisher pigs (Schinckel and deLange, 1996; Smith et al., 1999; Schinckel et al., 2002; Green et al., 2003). Growth rates observed in those studies ranged from 680 to 910 g/d for pigs of 116 days of age (age of pigs in the AL-group) and from 700 to 970 g/d for pigs of 133 days of age (age of pigs in the CL-group). In comparison, growth rates observed in the current study were relatively low for pigs in the AL-group, which may be due to a number of factors. One possible explanation is that manual weight measurements may have caused a short-term reduction in feed intake and thus growth rates.

Descriptive plots indicated that mean weights in both feeding systems were affected by the time of day, and these changes were significant in the multivariate model. For the CL-group, the magnitude of mean weight change between sequential weight measurements was in accordance with the frequency of meal deliveries. In contrast, mean weight in the AL-group increased steadily throughout the day and dropped over night. The steady increase observed in the AL-group corresponds well with the preferential diurnal feeding of pigs documented in previous studies (De Haer and Merks, 1992; Hyun et al., 1997; Quiniou et al., 2000; Collin et al., 2001; Georgsson and Svendsen, 2001). Studies have repeatedly shown that there is a peak of feeding activity in the morning and afternoon (Nielsen et al., 1995; Bornett et al., 2000; Hyun and Ellis, 2002;

O'Connell et al., 2002). The greater peak in feed intake generally occurs in the afternoon (Morrow and Walker, 1994; Bornett et al., 2000; O'Connell et al., 2002). Increased feeding activity in the afternoon was supported by the current study where live weight of ad libitum fed pigs showed the greatest increase between 1400 and 1730.

This study also investigated the impact of time of day on the variability in live weight. The results showed that there was no consistent pattern in coefficient of variation in live weight (CV) over time in either feeding system. Furthermore, the range in CV within a day did not exceed 0.8% for either feeding system. Therefore, it was concluded that the effect of time of day on variability in live weight is of minor importance.

Multivariate analysis was used to determine confounding effects of other factors on the effect of time of day on weight change. Correlations of multiple measurements taken on the same pig were accounted for using a repeated measures linear mixed model. Multivariate analysis was stratified by feeding system because feeding system was not a factor of interest in this study.

It was not possible to include both pen and year of replicate in this model because a hierarchically nested relationship existed between pen (lower level) and year of replicate. Dohoo *et al.* (2003) recommended to include the lower level factor in the model since it provides more detailed information. The effect of pen incorporates both year and pen effects. Therefore, the pen effect incorporates pen effects such as group size and feeder trough space as well as year effects including changes in farm management or environmental conditions

For each feeding system, there were two significant interactions. First, there was an interaction between time of day and day for both groups. Secondly, an interaction was present between time of day and pen for the CL-group and between start weight and pen for the AL-group. All interactions were biologically plausible. However, inclusion of these interactions in the model raises issues with interpretation. All but one interacting variable (start weight) were four-level categorical variables. The inclusion of two interactions with two four-level categorical variables would have resulted in 18 interaction terms. This number of predictors would have been too large given the relatively small data set ('overfitting'). Furthermore, under the null hypothesis, one out of twenty interaction terms ($P < 0.05$) would be expected to be significant by chance alone (Thrusfield, 2005). Therefore, for simplicity, it was decided to present regression coefficients for the main effect model only. Presenting the main effect model only was considered appropriate since the primary interest of this analysis was to identify patterns of diurnal weight change, not to estimate the magnitude of the effect of time of day. However, parameter estimates should be interpreted with caution, since the main effect model adjusts for confounding, not for interaction. Hence, it assumes that the association of X_1 to Y is the same across all levels of X_2. Interactions will be addressed after the discussion of the main effect model.

There was a significant effect of pen in the model for the AL-group. The model predicts that after adjusting for other variable in the models, pigs in the pens used in the 2004 replicate were lighter than the pigs in the pens used in the 2003 replicate. This is in agreement with significantly lower start weight of pigs in the 2004 replicate. Other factors such as different group sizes per pen and thus feeder to pig ratio may have contributed to the significant pen effect. Under ad libitum feeding, reduction of feeder space may decrease individual feed intake (Georgsson and Svendsen, 2001) and change feed intake patterns (Botermans et al., 2000; Georgsson and Svendsen, 2002). Korthals (2000) modelled feeder usage patterns when feeding different numbers of pigs (21, 31, and 45 pigs) from a four-space feeder. Based on the model results, the author concluded that 12 to 14 pigs could be fed adequately per feeder space without effects on individual feed intake. Similarly, Nielsen *et al.* (1995) observed no effect on feeding behaviour when feeding 15 pigs from a single-space feeder compared to smaller group sizes. For the AL-group, the maximum number of pigs per feeder space in the present study was six, indicating a non-competitive environment amongst pigs within a pen. Therefore, it was unlikely that the significance of the variable pen was attributable to differences in group size. Although pigs in the CL-group were housed in different sheds, the variable coding for pen was not significant for the CL-group.

Pig weight at the start of the observation period (start weight) allowed adequate prediction of weight measurements since it was the only continuous variable in the model. Exclusion of this variable from the model resulted in a poorly fitting model. Adjusting predicted weight by start weight accounted for the natural variation in pig weight. Predicted weight was almost perfectly associated with start weight (beta = 0.98 kg).

The significant interaction between day and time of day for both feeding systems indicates that the effect of time of day varied between days. An interaction between day and time of day may be expected if manual weighing had altered feeding behaviour. On the other hand, the interaction may have been caused by variability in feeding behaviour of pigs between days. The effect of time of day varied more between days for pigs in the AL-group compared to pigs in the CL-group. This suggests that meal feeding may have had a standardizing effect on feeding behaviour and thus gut fill in pigs of the CL-group. In contrast, it is accepted that ad libitum fed pigs show high variation in feed intake patterns. For instance, the number of feeder visits per pig ranged from 3 to 69 per day in the study of Young and Lawrence (1994) and from 18.8 to 80.3 in the study of Morgan *et al.* (2000). Therefore, variability in diurnal weight changes between days is likely to occur, particularly in ad libitum fed pigs.

The results clearly indicate that time of day is important when assessing mean weight. In contrast, time of day appears not to be important when the aim is to assess weight variation. The difference of weight change patterns observed between feeding systems was in agreement with feed deliveries in the CL-group and expected feed intake pattern of pigs in the AL-group. Therefore, results provide an indirect support of the hypothesis that gut fill represents a source of error in weight measurements. It is hypothesized that the importance of time of the day on weight measurements may be generalized to other farms, age groups, and seasons regardless of expected differences in feed intake patterns.

In conclusion, weight varied within a day, and these variations appeared to be associated with feed intake patterns. Therefore, results provide an indirect indication that variability in gut fill represents a source of error in live weight measurements. The results showed that diurnal fluctuation in weight due to the error of gut fill can be reduced by keeping weighing time as well as feeding time in a CL-situation constant. However, standardization of weighing time appears insufficient to eliminate variability in pig weights due to biological factors such as gut fill, particularly if pigs are fed ad libitum. Hence, the following chapter investigates whether feed withdrawal is effective in reducing between-pig variation in live weight.

Chapter 5 Effect of feed withdrawal on between-pig variation in live weight and average daily gain

Abstract

AIM: To investigate if overnight feed withdrawal is effective in reducing between-pig variation in live weight and average daily gain.

METHODS: The experiment used weaner, grower, and finisher pigs, which were housed on a commercial pig farm in New Zealand. On this farm, weaner and grower pigs were fed ad libitum, while finisher pigs were fed four times a day via a computerized liquid feeding system. The experiment was conducted in two overnight periods (day 0, day 21). On both days, the duration of the experimental period was 11 hours for weaners and 17 hours for growers and finishers. Pens of pigs were randomly assigned to either a treatment or control group. The treatment pens had feed withdrawn, whereas control pens were managed in accordance with normal farm practices. Pigs were weighed individually at the start and end of each experimental period. This resulted in four weight measurements: (i) weight on day 0 prior to the experimental period (weight 1), (ii) weight on day 1 after the experimental period (weight 2), (iii) weight on day 21 prior to the experimental period (weight 3), and (iv) weight on day 22 after the experimental period (weight 4). Average daily gain (ADG) over the study period was calculated using weight 1 and weight 3 (start-to-start ADG), and weight 2 and weight 4 (end-to-end ADG). Mean pig weight and standard deviation were calculated for the four weight variables and the two measures of ADG. Results were presented stratified by treatment group, production stage, and experimental period. Changes in mean and standard deviation were expressed as a percentage of the respective variable measured at the start of the experimental period. The paired t-test and the Pitman-Morgan test were used to assess differences in means and variances.

RESULTS: The experiment included 118 weaner pigs, 102 grower pigs, and 103 finisher pigs. Feed withdrawal was associated with a reduction in mean live weight and mean ADG for pigs of all production stages ($P < 0.001$). For grower and finisher pigs, feed withdrawal was associated with reduced variability in live weight by between 4.0% and 11.1% and in ADG by between 11.3% and 11.5% ($P < 0.05$). The effect on variability in live weight and ADG was inconsistent in unfed weaner pigs. Pigs in the control groups showed similar or higher variability

in live weight and ADG when measurements were taken at the end compared to the start of each experimental period.

CONCLUSION: Results indicate that overnight feed withdrawal is effective in reducing between-pig variation in live weight and average daily gain of grower and finisher pigs. Based on results from other authors, it was hypothesized that this effect was associated with reduced between-pig variation in gut fill. However, the observed effect needs to be replicated on other farms, before general recommendations can be made. It is not recommended to withdraw feed from weaner pigs.

5.1 Introduction

Pig weight measurements represent key performance parameters when monitoring growing herd performance. Live weight measurements include the weight of intestinal contents, which may reach up to 10% of live weight (Stranks et al., 1988; Kyriazakis and Whittemore, 2006). Chapter 4 applied multivariate techniques to assess the effect of standardizing weighing time on live weight of finisher pigs fed ad libitum or via a computerized liquid feeding system. The results showed that standardization of weighing time could be used to reduce variability in pig weights due to biological factors such as gut fill, thus reducing the measurement error. However, significant interaction terms between time of day and day indicated that weight changes of individual pigs were not consistent between days. This was particularly true for pigs fed ad libitum. It is known that feed intake patterns of ad libitum fed pigs are highly variable (De Haer et al., 1993c; Hyun et al., 1997), which may explain observed differences in weight change patterns between days of ad libitum fed pigs.

Short-term feed withdrawal is another method that can be used to reduce variation in weights due to gut fill (Lawrence, 2002; Scanes, 2003). Several studies exist assessing the effect of feed withdrawal on mean live weight (Eikelenboom et al., 1991; Fernandez et al., 1995a; Fernandez et al., 1995b; De Smet et al., 1996; Brown et al., 1999; Murray et al., 2001; Beattie et al., 2002; Morrow et al., 2002; Bidner et al., 2004). However, none of the studies specifically assessed the effect of feed withdrawal on variability in live weight. This chapter tested the hypothesis that overnight feed withdrawal may be effective in reducing between-pig variation in live weight and average daily gain. A control group was included to verify that the effect on between-pig variation was attributable to the effect of treatment.

5.2 Materials and methods

5.2.1 Farm management

The reader is referred to Chapter 3 for a detailed description of the farm management. Briefly, the studied farm managed weaned pigs in batches using a three-stage production system: i) weaner, ii) grower, and iii) finisher stage. Pigs in each batch were divided amongst six pens in the weaner shed (20 pigs per pen), eight in the grower shed (13 pigs per pen), and up to ten pens in the finisher shed (10 to 13 pigs per pen). It was routine farm management to allocate pigs to pens as follows: At weaning, pigs were sized to match pen mates, whilst at subsequent transfers the smallest pigs from each pen were removed and mixed to create new pens.

Weaner and grower pigs were fed ad libitum from one double-sided wet-dry feeder. Finisher pigs used for this experiment were fed four times a day via a computerized liquid feeding system. The feeding times for the computerized liquid feeding system were 0830, 1015, 1430, and 2000. All pigs had continuous access to water.

5.2.2 Study design

The Animal Ethics Committee of Massey University gave ethics approval for this experiment. Pigs from three different production stages (weaner, grower, and finisher pigs) were included in the experiment. Pairs of weaner and grower pens adjacent to the same feeder and individual finisher pens were randomly assigned to either a treatment (unfed) or control group (fed).

The experiment was conducted in two overnight periods (day 0, day 21). On both days, the duration of the experimental period was 11 hours for weaners and 17 hours for growers and finishers. During both overnight periods, the treatment group had feed withdrawn, whilst controls were managed in accordance with normal farm practices. For finisher pigs fed via the computerized liquid feeding system, routine meal delivery at 1015 was postponed for both treatments and controls until all pigs had been weighed.

Pigs were weighed individually at the start and end of each experimental period. Weaners were weighed last in the afternoon (weight 1 and 3: 1900) and first in the morning (weight 2 and 4: 0600) to reduce the time of feed withdrawal to eleven hours. Growers (weight 1 and 3: 1500; weight 2 and 4: 0800) were weighed prior to finishers both times (weight 1 and 3: 1700; weight 2 and 4: 1000). Pens of control and treatment pigs were weighed alternately. The order, in which pens were weighed at the first weight measurement, was kept constant at subsequent measurements.

Sample size was determined using http://calculators.stat.ucla.edu/powercalc/ to detect a 4.2 kg difference in mean and a 0.41 kg difference in standard deviation in finisher weights (based on farm data) using a power of 80% and a one-sided significance level of 0.05. It was concluded that 47 treatment and 45 control animals would be required to detect a difference between measurements taken at the start and end of each experimental period.

5.2.3 Statistical analysis

The study design resulted in four weight measurements: (i) weight on day 0 prior to the experimental period (weight 1), (ii) weight on day 1 after the experimental period (weight 2), (iii) weight on day 21 prior to the experimental period (weight 3), and (iv) weight on day 22 after the experimental period (weight 4). Average daily gain (ADG) over the study period was calculated using weight 1 and weight 3 (start-to-start ADG), and weight 2 and weight 4 (end-to-end ADG).

For each production stage and treatment group, normality of pig weights and ADG was assessed via visual inspection of frequency histograms. Mean and standard deviation was calculated for each of the four weights and the two ADG variables. Differences between experimental groups in mean live weight and variance in live weight at study start were assessed using the two-sample *t*-test and the Levene's test, respectively.

Measurements at the start and end of each experimental period were taken on the same set of animals, thus representing paired measurements. Three sets of paired variables were analysed that is, weight 1 and weight 2, weight 3 and weight 4, and start-to-start ADG and end-to-end ADG. The change in mean and standard deviation for each set of paired variables was expressed as a percentage of the respective variable measured at the start of the experimental period. For each production stage and treatment group, normality of differences in mean pig weight and ADG was assessed via visual inspection of frequency histograms. Differences in mean between paired measurements were assessed using a two-sided paired *t*-test. Variability between paired measurements was compared by means of the Pitman-Morgan's *t*-test for correlated variances (Morgan, 1939; Pitman, 1939). The Pitman-Morgan method is used to test the correlation between the sum and the difference of the correlated measurements, with zero correlation corresponding to the equality of the two variances. Results were presented stratified by treatment group, production stage, and experimental period.

Analysis was conducted in SAS 9.1. Level of significance was set at 0.05.

5.3 Results

The experiment included 323 pigs from six weaner, eight grower, and eight finisher pens. Age at study start was 34 days for weaner, 62 days for grower, and 90 days for finisher pigs. One finisher pig with rectal prolapse was excluded from the data set. Eleven pigs were lost to follow-up between the first (day 0/1) and second experimental period (day 21/22) due to death (five unfed weaners, one fed weaner), and transfer to hospital pens or marketing (five fed finishers). Consequently, weights 1 and 2 were derived from 322 pigs, whilst weight 3, weight 4, and average daily gain (ADG) were derived from 311 pigs.

At the start of the study, control finisher pigs were 3.09 kg heavier than treatment finisher pigs ($P = 0.03$). A difference in start weights between fed and unfed grower pigs was marginally significant ($P = 0.07$). Variance in pig weights at study start was greater in fed compared to unfed pigs at both the grower ($P = 0.03$) and finisher stage ($P < 0.001$).

For unfed pigs of all production stages, mean live weight (Table 5.1) and mean ADG (Table 5.2) were reduced at the end of each experimental period. For grower and finisher pigs, feed withdrawal was associated with a reduction in variability in live weight by 4.0% to 11.1% (Table 5.3). Similarly, variability in ADG (Table 5.4) was 11.3% to 11.5% lower in grower and finisher pigs, respectively, when calculations were based on end weights (end-to-end ADG) compared to start weights (start-to-start ADG). For weaner pigs, the effect of feed withdrawal on variability in live weight and ADG was inconsistent. Pigs in the control groups showed similar or higher variability in live weight and ADG when measurements were taken at the end compared to the start of each experimental period.

Table 5.1. Differences in mean pig weight at the start and end of the two experimental periods by group, production stage, and day of replicate. Differences in mean pig weight were assessed using the paired *t*-test.

Group	Production stage	Day	Number of pigs	Mean weight (kg)		Change (%) [a]	P-value
				Start	End [b]		
Feed withdrawal							
	Weaner	0	52	9.9	9.7	-2.0	<0.001
		21	47	21.4	20.5	-4.2	<0.001
	Grower	0	51	31.5	30.2	-4.1	<0.001
		21	51	49.2	46.7	-5.1	<0.001
	Finisher	0	52	56.1	53.8	-4.1	<0.001
		21	52	73.9	70.3	-4.9	<0.001
No feed withdrawal							
	Weaner	0	66	9.9	9.9	0.0	0.77
		21	65	21.0	21.3	1.4	0.04
	Grower	0	51	32.6	33.4	2.5	<0.001
		21	51	51.5	51.9	0.8	0.01
	Finisher	0	50	59.2	59.3	0.2	0.74
		21	45	75.8	75.7	-0.1	0.47

[a] Percentage change in mean relative to mean weight at start.
[b] The experiment was conducted in two overnight periods (day 0, day 21), which covered 11 hours for weaner and 17 hours for grower and finisher pigs.

Table 5.2. Differences in mean average daily gain (ADG) of pigs depending on whether ADG was based on start (start-to-start) or end weights (end-to-end) of two experimental periods that were 21 days apart. Differences in mean were assessed using the paired *t*-test.

Group	Production stage	Number of pigs	Mean ADG (g/d)		Change (%) [a]	P-value
			Start-to-start [b]	End-to-end [c]		
Feed withdrawal						
	Weaner	47	544	516	-5.1	<0.001
	Grower	51	842	786	-6.7	<0.001
	Finisher	52	846	783	-7.4	<0.001
No feed withdrawal						
	Weaner	65	530	542	2.3	0.01
	Grower	51	901	880	-2.3	0.005
	Finisher	45	834	826	-1.0	0.48

[a] Percentage change in mean relative to mean start-to-start ADG.
[b] Each experimental period started at 1500, 1700, and 1900 for weaner, grower, and finisher pigs.
[c] Each experimental period ended at 0600, 0800, and 1000 for weaner, grower, and finisher pigs.

Table 5.3. Differences in variability (expressed as standard deviation) of pig weights at the start and end of two experimental periods by group, production stage, and day of replicate. Differences in variability were assessed using the Pitman-Morgan test.

Group	Production stage	Day	Number of pigs	Standard deviation (kg)		Change (%) [a]	P-value
				Start	End [b]		
Feed withdrawal							
	Weaner	0	52	2.1	2.0	-4.8	<0.001
		21	47	3.6	3.5	-2.8	0.10
	Grower	0	51	2.6	2.4	-7.7	0.001
		21	51	4.5	4.0	-11.1	<0.001
	Finisher	0	52	5.0	4.8	-4.0	0.048
		21	52	6.7	6.2	-7.5	<0.001
No feed withdrawal							
	Weaner	0	66	1.7	1.7	0.0	0.72
		21	65	3.3	3.6	9.1	0.004
	Grower	0	51	3.6	3.6	0.0	0.98
		21	51	4.6	4.9	6.5	0.01
	Finisher	0	50	8.2	8.2	0.0	0.72
		21	45	8.6	8.7	1.2	0.62

[a] Percentage change in standard deviation relative to standard deviation at start.
[b] The experiment was conducted in two overnight periods (day 0, day 21), which covered 11 hours for weaner and 17 hours for grower and finisher pigs.

Table 5.4. Differences in variability (expressed as standard deviation) of average daily gain (ADG) depending on whether ADG was based on start (start-to-start) or end weights (end-to-end) of two experimental periods that were 21 days apart. Differences in variability were assessed using the Pitman-Morgan test.

Group	Production stage	Number of pigs	Standard deviation in ADG (g/d)		Change (%) [a]	P-value
			Start-to-start [b]	End-to-end [c]		
Feed withdrawal						
	Weaner	47	98.7	96.8	-1.9	0.56
	Grower	51	133.2	117.9	-11.5	0.006
	Finisher	52	141.2	125.2	-11.3	0.01
No feed withdrawal	Weaner	65	91.6	110.2	20.3	<0.001
	Grower	51	112.8	120.2	6.6	0.29
	Finisher	45	164.1	162.3	-1.1	0.86

[a] Percentage change in standard deviation relative to standard deviation of start-to-start ADG.
[b] Each experimental period started at 1500, 1700, and 1900 for weaner, grower, and finisher pigs.
[c] Each experimental period ended at 0600, 0800, and 1000 for weaner, grower, and finisher pigs.

5.4 Discussion

To the author's knowledge, this was the first study testing the effect of feed withdrawal on between-pig variation in live weight and average daily gain. The experiment used a control group to verify that the effect on between-pig variation was attributable to the effect of treatment. Two experimental periods were conducted with the same pigs on day 0 and day 21 to assess the effect of feed withdrawal on mean and variability in average daily gain (ADG). Average daily gain is the most common parameter calculated from weight measurements. Therefore, it was of interest whether variability in ADG over the study period was affected depending on whether it was calculated from weights at the start (start-to-start ADG) or the end of each experimental period (end-to-end ADG). Care should be taken when extrapolating beyond the study population as the data were derived from one farm.

The duration of both experimental periods was 11 hours for weaners and 17 hours for growers and finishers. A shorter feed withdrawal period was chosen for weaner pigs due to their small gut capacity and immature gastrointestinal system (Pluske et al., 1997). Therefore, feed withdrawal is more likely to have negative effects on the wellbeing of weaner compared to older pigs. A feed withdrawal period of 17 hours may be applied under commercial conditions, assuming that feeders are turned off when staff leaves the farm (1600), and pigs are then weighed at the start of the next working day (0900).

The actual duration of feed withdrawal for finisher pigs in the treatment group was longer than 17 hours as they received their last meal two and a half hours prior to the first weight measurement of each period. Similarly, individual weaner and grower pigs, which were fed ad libitum, may not have eaten for several hours prior to feed withdrawal. Hence, gut fill losses may have occurred prior to the start of the experimental periods in both experimental groups.

The study design did not allow comparisons to be drawn between pigs from different production stages. First, weighing times differed between production stages that is, weaners were weighed at 1900 and 0600, growers at 1500 and 0800, and finishers at 1700 and 1000. Secondly, weaner and grower pigs were fed ad libitum, whilst finisher pigs received feed via a computerized liquid feeding system. Furthermore, care has to be taken when comparing results between treatment and controls as the attempt to achieve randomization by allocating pens to treatment groups at random was unsuccessful. This was indicated by significant weight differences between groups at study start. Instead of assessing differences between treatment groups, comparisons were made between weights taken on the same animal (paired measurements), thus using each pig as its own control.

Paired measurements are likely to be correlated, thus not meeting the assumption of independence of many statistical techniques. The paired *t*-test for mean differences is a standard technique, which removes the problem of correlation between paired data by testing whether the difference in means is different from zero. In contrast, testing for homogeneity of variances is not routinely performed for paired data. This may partly explain why the effect of feed withdrawal on variability in pig weights has not been assessed previously. The Pitman-Morgan method (Morgan, 1939; Pitman, 1939) tests the correlation between the sum ($Y_{1i} + Y_{2i}$) and the difference ($Y_{1i} - Y_{2i}$) of the correlated measurements, with zero correlation corresponding to the equality of the two variances. This approach leads to uncorrelated pairwise sums ($e_{1i} + e_{2i}$) and differences ($e_{1i} - e_{2i}$) of errors. Jones *et al.* (2007) used the current data set to compare estimates of the treatment effect between the Pitman-Morgan method, method of moments, and Bayesian method. Jones concluded that the Pitman-Morgan method performs well provided that the treatment effect is not too large.

Feed withdrawal was associated with a reduction in mean live weight by 2.1% to 4.2% in weaner pigs and 4.1% to 5.1% in grower and finisher pigs. The shorter feed withdrawal period of weaner pigs (11 hours) compared to grower and finisher pigs (17 hours) may explain the smaller effect in weaner pigs. In comparison to the current experiment, Beattie *et al.* (2002) found lower live weight losses in finisher pigs after 12 hours (1.2%) and 20 hours of feed withdrawal (3.3%). In contrast, live weight losses of 62 kg-pigs after 18 hours of feed withdrawal were higher (6.1%) in the study of Warris and Brown (1983). Differences in study findings may have occurred due to several factors such as differences in initial gut fill levels. The study by Beattie recorded initial weights of ad libitum fed pigs at 0800 compared to afternoon measurements in the current study. Therefore, initial levels of gut fill were likely to be lower in the study by Beattie. Warris measured initial live weight one hour after their morning meal, whereas finisher pigs in the current study were weighed 2.5 hours after their last meal. Hence, initial gut fill levels of pigs in the study of Warris were likely to be higher than in the present study. It may be concluded that live weight losses were in the expected range of live weight losses.

Unfed grower and finisher pigs showed a significant reduction in variability in live weight by 4.0% to 11.1% and in average daily gain by 11.3% to 11.5%. These results support the hypothesis that feed withdrawal may be effective in reducing variability in live weight and average daily gain. In contrast, the effect of feed withdrawal on variability in live weight and average daily gain was inconsistent in weaner pigs. The lack of a consistent effect in weaner pigs may be due to a number of factors. Firstly, the duration of feed withdrawal was six hours less in weaner pigs than in grower and finisher pigs, and this may have been insufficient to produce a significant effect. Secondly, sample size may have been too small to detect a significant effect, since sample sizes were derived from power calculations for detecting differences in finisher pig weights.

Mean live weight of fed pigs was similar or higher at the start compared to the end of each experimental period. This is in agreement with experimental results from Chapter 4, where finisher pigs were weighed at 0700, 1030, 1400, and 1730 over a four-day period. In the latter experiment, ad libitum fed pigs showed similar weights at 1500 compared to 0800 the next day. Similarly, mean weight of pigs fed via a computerized liquid feeding system were likely to be similar between 1700 and 1000 the next day considering that one meal instead of two meals were delivered between 0700 and 1030 in the current experiment.

Fed pigs showed similar or higher variability in live weight and average daily gain at the end compared to the start of the experimental period. Reduction in between-pig variation in live weight and ADG of unfed grower and finisher pigs, in combination with the lack of effect in fed pigs, suggests that feed withdrawal is effective in reducing variability in live weight and ADG. The effect was observed in grower pigs fed ad libitum and in finisher pigs fed via a computerized liquid feeding system. Hence, the effect of short-term feed withdrawal on between-pig variation appears to be independent of feeding system.

Feed withdrawal may have caused a reduction in mean and variability in measurements of unfed pigs through changes in gut fill, body mass, and measurement error. Measurement error may be assumed to represent a random error, thus not causing a consistent reduction in mean and variability in measurements. In contrast, loss in body mass may have contributed to the observed reduction in mean live weight, and possibly variability. Studies differ in their findings, after what time feed withdrawal induces a loss in body mass. Murray *et al.* (2001) detected significant carcass weight losses after 15 hours of feed withdrawal and 260 km transport. In the latter study, transport may have confounded the effect of feed withdrawal on carcass weight. This is supported by Mayes *et al.* (1988), who found that 24 hours fasting in combination with 700 km transport resulted in 1.4% greater carcass weight losses than fasting alone. In contrast to Murray, no effect on carcass weight was reported in the study of Beattie *et al.* (2002) after a 12- or 20-hour fast, and by Bidner (2004) after a 12- or 36-hour fast. Warris and Brown (1983) measured carcass weight of finisher pigs after 9, 18, 24, 33, and 48 hours and concluded that carcass weight decreases after 18 hours at a rate of 0.11% per hour. Hence, it may be assumed that 17 hours of on-farm feed withdrawal is likely to induce only minor losses of body mass. Therefore, it may be concluded that the observed reduction in mean live weight in unfed pigs was predominantly associated with losses of gastrointestinal contents.

A reduction in variability in live weight and average daily gain of unfed pigs may indicate that the proportion of live weight that is attributable to gut fill was more consistent between animals. A reduction in gut fill variability may be associated with a reduction in random error or systematic error. Systematic errors affect the validity of measurements, whereas random errors reduce precision (Noordhuizen et al., 2001).

Factors causing systematic differences in feed intake patterns and hence gut fill levels between individual pigs of the same group may lead to systematic errors in live weight measurements. For instance, there is evidence that light pigs exhibit different feeding behaviour in competitive feeding situations than their heavier counterparts (Georgsson and Svendsen, 2002). In the latter study, light pigs not obtaining sufficient access to feeders during daytime hours were more likely to eat during the night. Consequently, in competitive feeding situations, gut fill levels of light pigs are likely to change differently throughout the day, thus possibly causing systematic errors in individual pig weights. Systematic errors may be less likely to occur when the aim is to assess mean pig weight of a group of pigs and weighing time is kept constant.

Presented results suggest that feed withdrawal could be applied as a routine management strategy to reduce between-pig variation in live weight and average daily gain. However, several negative effects have been associated with feed withdrawal. Brumm *et al.* (2004) found that repeated out-of-feed events for 20 to 24 hours may increase variability in average daily gain up to market. Melnichouk (2002) suggested that feed withdrawal for 24 hours once a week may contribute to the development of gastric ulcers. Furthermore, there is evidence that feed withdrawal leads to increased fighting (Murray et al., 2001; Warriss, 2003). Therefore, longitudinal studies are recommended to investigate whether pigs show reduced growth performance or increased morbidity when they have feed withdrawn for 17 hours three times throughout production that is, at the start of the grower and finisher stage and prior to marketing.

Whilst feed withdrawal prior to weight measurements may be an option for grower and finisher pigs, withdrawing feed from newly weaned pigs is not recommended. First, the effect of feed withdrawal on variability in live weight and average daily gain was inconsistent in this age group. Secondly, gut capacity of weaner pigs is relatively small, thus producing minor errors. Thirdly, it is likely that weaner pigs are more susceptible to adverse effects of feed withdrawal. An increased health risk of feed withdrawal in weaner pigs may have been indicated by a numerically higher number of deaths in unfed (n = 5) compared to fed weaner pigs (n = 1). However, low observed counts did not allow testing this observation for significance.

In conclusion, results indicate that overnight feed withdrawal is effective in reducing between-pig variation in live weight and average daily gain of grower and finisher pigs. Based on results from other authors, it was hypothesized that this effect was associated with reduced variability in gut fill. However, the observed effect needs to be replicated on other farms, before general recommendations can be made. Furthermore, it needs to be investigated whether overnight feed withdrawal three times throughout production may have a negative effect on long-term performance or pig health. It is not recommended to withdraw feed from weaner pigs since feed withdrawal may pose an increased health risk in weaner pigs.

Chapter 6 Effect of sample size and sampling method on sampling error when sampling pens of grower and finisher pigs

Abstract

AIM: To compare the magnitude of the sampling error between (1) different sample sizes following random sampling, and (2) random sampling and purposive sampling when sampling two out of eight pens.

METHODS: This retrospective study analysed routinely collected weight records from a commercial New Zealand pig farm. The data set included 130 batches of pigs (Large White x Landrace) weaned weekly between December 2001 and June 2004. Sample weight records were available for each pen at transfer from the weaner to the grower shed and from the grower to the finisher shed. Eight finisher pens were randomly selected for finisher batches that included more than eight pens, in order to achieve a consistent number of eight pens across batches. For random sampling, one to seven pens were randomly selected from each batch and production stage. Random sampling was repeated five times. For purposive sampling, two pens were selected either by weight rank (lowest and highest as well as fourth and fifth highest weight rank) or by their pen location (grower batches only). True mean pig weight of an individual batch was calculated as the mean pig weight for all eight pens. For each sample, estimated mean pig weight of an individual batch was calculated as the mean pig weight of the selected pens. The magnitude of sampling error was expressed as the root-mean-squared error.

RESULTS: Increasing the portion of randomly selected pens continuously reduced the sampling error, but in a diminishing manner. Purposive sampling of two pens by their weight rank reduced sampling error by at least 65% compared to random sampling of two pens. On the contrary, purposive sampling of two pens by their location provided inconsistent results.

CONCLUSIONS: This analysis supports purposive sampling of weight ranked pens. However, purposive selection of pens is not recommended due to the unknown risk of obtaining biased samples. For random sampling, presented results may serve as a tool to guide decision makers in their quest to balance time and cost factors against the accuracy of sample weights. It is recommended to weigh half the batch following random sampling to obtain reliable estimates of overall batch performance.

6.1 Introduction

Pig weight records represent key performance parameters when monitoring growing herd performance. Therefore, maximizing accuracy of pig weight measurements enhances the effectiveness of the monitoring system. Producers often weigh a sample of pigs to draw inferences on the performance of the entire batch. This practice is effective in reducing costs of data collection, but it introduces sampling error thus affecting the accuracy of weight measurements. Therefore, it is important that producers are aware of the sampling error and how this error can be minimized. After investigating sources of measurement error in the previous two chapters, the current chapter assesses the magnitude of the sampling error when sampling pens from batches of pigs.

The main concern when selecting a sample is to ensure that sampling error is minimised. The sampling error represents the difference between the true value of the parameter in the study population and the value obtained from the sample. Sampling error includes error due to sampling bias and sampling variation (Henry, 1990). Sampling bias refers to the error introduced when the study population does not represent the target population resulting in population characteristics being under- or overemphasized (Delgado-Rodriguez and Llorca, 2004). In contrast, sampling variation is defined as the variation of multiple samples of the same size caused by the chance inclusion of individuals in the samples (Thrusfield, 2005). Hence, sampling variation represents a random error. The magnitude of this random error is measured by the variability that occurs when taking multiple random samples (De Veaux, 2008).

Sampling error depends on the method of sample selection and sample size (Sudman, 1976). Samples can be selected using either probability sampling or non-probability sampling. Probability sampling, also referred to as random sampling, assumes that every element in the population has a known non-zero probability of being selected (Dohoo et al., 2003). If every element has an equal chance of being selected, it is called a simple random sample. Random samples eliminate sampling bias since all units have an equal chance of being selected. Hence, random sampling reduces the sampling error to the sampling variation. For sufficiently large sample sizes ($n \geq 30$), the sampling error of simple random samples can be estimated by the standard error of the sample, which approximates the sampling variation. Therefore, when using random sampling, the error declines proportionally with the square root of sample size (De Veaux, 2008).

Non-probability sampling includes judgement sampling, convenience sampling, and purposive sampling (Dohoo et al., 2003). The term purposive sampling is subsequently used refer to any type of non-probability sampling. Purposive sampling is prone to introduce sampling bias. Therefore, inferences cannot be drawn on the population of interest. Furthermore, the size of the sampling errors cannot be estimated a priori and cannot be reduced by increasing sample size.

Some empirical guidelines are given by specialized growing herd software packages for selecting appropriate samples. The PigWIN program (PigWIN® at http://www.pigwin.com) recommends weighing 20 pigs per batch following random sampling to assess batch performance. In comparison, Porkma$ter (1997) recommends weighing at least two representative pens per batch (purposive sampling). However, to the author's knowledge no published data exist clearly investigating the effect of sampling method and sample size on sampling error when sampling pens from batches of pigs. Hence, an analysis was conducted using real farm data to simulate different sampling methods and sample sizes of pens. The aim was to compare the magnitude of the sampling error between (1) different sample sizes following random sampling, and (2) random sampling and purposive sampling when sampling two out of eight pens.

6.2 Materials and methods

6.2.1 Farm management

This analysis was based on a retrospective dataset that included routinely collected weight records from a commercial 270-sow farrow-to-finish farm in the North Island, New Zealand. The farm management is described in detail in Chapter 3. Briefly, the farm weaned Large White x Landrace pigs at approximately four weeks of age and managed them as batches using a three-stage production system (weaner, grower, and finisher stage). Pigs were managed as weaner pigs for 40 days, grower pigs for 38 days, and finisher pigs for approximately four weeks until marketing.

Weaner and grower batches were housed in a single shed, whereas finisher batches were placed in one of four finisher sheds with different housing capacities (Table 6.1). Finisher pigs were distributed amongst eight pens when allocated to shed A, nine pens when allocated to shed B, and ten pens when allocated to sheds C and D. The latter two finisher sheds were of the same design. An additional shed (shed E) was used to house individual grower and finisher pens from intermittent batches. Pens housed in this latter shed were not considered for the current analysis.

It was routine farm management to allocate pigs to pens as follows: at weaning, pigs were sized to match pen mates. At subsequent production stages, the number of pens per batch increased between production stages (Table 6.1). Therefore, the smallest pigs from each pen were mixed to create new pens. The remainder of pigs in each pen was moved to pens of the next production stage as one group.

Table 6.1. Housing capacity of sheds used at different production stages to accommodate growing pigs on a commercial New Zealand pig farm.

Production stage	Shed	Number of batches per shed	Number of pens per batch	Number of pigs per pen
Weaner	W	6	6	20
Grower	G	6	8	13
Finisher	A	1	8	13
	B	2	9	13
	C	2	10	10
	D	2	10	10

Farm staff weighed all grower pens three days after pigs were transferred from the weaner to the grower shed. Weights for all finisher pens were recorded at the time of transfer from the grower to the finisher shed. Weight measurements were taken in the late morning. At each weighing, pigs were moved out of their pen as a group and weighed in one or two lots. The resolution of scales was 0.5 kg.

6.2.2 Data management

Farm staff recorded date of weighing, total pig weight per pen, and number of pigs per pen on handwritten pen cards. The producer entered the data with the respective batch and pen identifier into an Excel worksheet. The investigator imported all data into a customized database (Microsoft Access, 2003). Mean pig weight was calculated for each pen. Data were inspected for outliers and data entry errors. If data errors were suspected, electronic records were compared to the handwritten pen cards and in case of inconsistencies were corrected.

6.2.3 Exclusion criteria

Unbiased comparisons of sampling errors across batches required a consistent number of pens across batches. All but one grower batch had pigs distributed amongst eight pens. The grower batch with less than eight pens was excluded for both production stages.

The number of finisher pens per batch ranged from eight to ten pens depending on shed location. Therefore, eight finisher pens were randomly selected from finisher batches including nine (shed B) or ten pens (sheds C and D). Exclusion of pens was systematic over time since finisher batches were allocated to sheds in a consistent order. For subsequent analysis, a batch of pigs refers to the eight pens used for analysis unless noted otherwise.

6.2.4 Sampling procedure

The retrospective data set was used to simulate random and purposive sampling of pens from each batch. For random sampling, one to seven pens were randomly selected without replacement per batch and production stage. The same procedure was repeated five times. Random numbers were generated using Microsoft Office Excel 2003.

For purposive sampling, two pens were selected either by their weight rank or by their pen location. When selecting pens by their weight rank, all pens within a batch were ranked according to their mean pig weight. The pair of pens with the lowest and highest weight rank as well as the pair of pens with the fourth and fifth highest weight rank was selected.

When selecting pens by their location, four different pairs of pen locations were randomly selected without replacement for grower data. Selection of pens by their location was not performed for finisher data for two reasons. Firstly, finisher sheds differed in their housing capacity so that finisher pen location could not be considered consistent across batches. Secondly, eight finisher pens were randomly selected from finisher batches with more than eight pens. Therefore, the same pen location would not be consistently present across batches. The total number of samples (random and purposive) was 41 for grower data and 37 for finisher data.

6.2.5 Calculation of variables

True mean pig weight of an individual batch was calculated by dividing the total weight for all eight pens by the total number of pigs in these pens. Between-pen variation in mean pig weight within a batch was expressed as the coefficient of variation in mean pig weight of pens within batch i (CV_i). The mean of CV_i was calculated across batches (CV_{mean}).

For each sample, the estimated mean pig weight of an individual batch was calculated by dividing the total pig weight of all selected pens by the total number of pigs in these pens. Therefore, the grower and finisher data set included 41 and 37 estimated mean pig weights, respectively. The portion of selected pens was calculated for each sample.

6.2.6 Data analysis

True mean pig weight, number of pigs for all eight pens, number of pigs per pen, and CV_i were tested for normality by visual inspection of frequency distributions.

Non–normally distributed variables were summarised using median and percentiles. Normally distributed variables were summarised using mean and 95% confidence interval of the mean.

Between-pen variation within a batch has a large effect on sampling variation. Therefore, three effects on CV_i were tested for significance. First, CV_i was regressed against time to assess the presence of a linear time trend. The Wald test was used to assess the significance of the linear trend. Secondly, the effect of finisher shed on CV_i was assessed using one-way ANOVA. Finisher sheds C and D were combined into one categorical variable since they shared the same housing capacities. Thirdly, a paired *t*-test was used to determine whether there was a significant difference in mean pig weight within a batch and CV_i due to exclusions of pens from finisher batches originally including more than eight pens. The paired variables were derived from (1) the original number of all pens per batch and (2) the eight randomly selected pens per batch.

Scatterplots of true mean pig weight versus estimated mean pig weight were produced for the first of the five repetitions of random sampling stratified by sample size. Scatterplots for the same variables were created for purposive sampling stratified by sampling method.

The root-mean-squared error (RMSE) was chosen as the measure of sampling error. For each sampling fraction and sampling method, it was calculated as:

$$(1) \quad RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\text{True mean pig weight}_{\text{i}} \text{ - Estimated mean pig weight}_{\text{i}})^2} \ ,$$

where n represents the total number of batches. The root-mean-squared error was expressed as a percentage of mean pig weight of all batches (%RMSE).

The root-mean-squared errors derived from all five repetitions of random sampling were plotted against the portion of selected pens. Logarithmic regression lines (Y = a + b ln(x)) and their 95% prediction intervals were fitted. Resulting logarithmic equations were used to predict root-mean-squared errors for each 0.1 increase in portion of selected pens. All results were stratified by production stage.

Statistical analysis was performed in SAS 9.1. Graphics were produced in R for Windows (Version 2.3.1). Level of significance was set at 0.05.

6.3 Results

6.3.1 Descriptive results

The original dataset consisted of 130 batches of pigs weaned weekly between December 2001 and June 2004. One batch with only seven grower pens was excluded from the dataset. All remaining 1032 grower pens (13 036 pigs) were used for the analysis. Eighty-one percent of the 129 finisher batches included more than eight pens. Hence, 14.7% of finisher pens (n = 1 210) and 14.0% of finisher pigs (n = 12 729) were excluded from the analysis.

Median number of pigs in all eight pens was 102 pigs (IQR: 99 to 104 pigs) for grower and 82 pigs (IQR: 79 to 91 pigs) for finisher batches. The median number of pigs per grower and finisher pen was 13 (min: 6 pigs, max: 17 pigs) and 10 (min: 7 pigs; max: 14 pigs), respectively. True mean pig weight was approximately normally distributed for grower (Figure 6.1) and finisher batches (Figure 6.2) with a mean of 33.0 kg (95% CI: 32.7 to 33.3 kg) and 64.5 kg (95% CI: 64.1 to 65.0 kg), respectively.

The mean coefficient of variation in mean pig weight of pens within a batch (CV_{mean}) was 9.7% (95% CI: 9.2 to 10.1%) for grower and 6.6% (95% CI: 6.3 to 6.9%) for finisher batches. A linear long-term trend for coefficient of variation in mean pig weight of pens within a batch (CV_i) was not significant for either grower ($P = 0.26$) or finisher batches ($P = 0.21$). The effect of finisher shed on CV_i was not significant (F-ratio = 1.75, df = 2, $P = 0.18$) (Table 6.2). Exclusion of finisher pens from batches including more than eight pens did not affect either mean true mean pig weight ($P = 0.87$) or CV_{mean} ($P = 0.14$).

6.3.2 Random sampling

Scatter plots of true mean pig weight versus estimated mean pig weight stratified by sampling fraction are displayed in Figure 6.3 for grower and Figure 6.4 for finisher batches. As the portion of randomly selected pens increased, the scatter of estimated mean pig weight decreased, gradually approximating the line of perfect fit. Figure 6.5 and Figure 6.6 depict the decrease in root-mean-squared error

(RMSE) with sample size for grower and finisher batches, respectively. When increasing the portion of selected pens, RMSE decreased logarithmically. Fitting logarithmic lines to RMSE's of all five random sampling repetitions yielded narrow prediction intervals. Resulting equations are given for grower and finisher batches, respectively, as follows:

(1) RMSE (%) = 0.78 – 3.94 × ln(Portion of selected pens) $R^2 = 0.98$,

(2) RMSE (%) = 0.46 – 2.81 × ln(Portion of selected pens) $R^2 = 0.98$,

where RMSE (%) represents the root-mean-squared error expressed in percent of the mean true mean pig weight of all batches. Predicted sampling errors of finisher batches were lower than of grower batches. The maximum difference in sampling errors between grower and finisher batches was 2.6% at the smallest investigated sample size.

6.3.3 Purposive sampling

Scatter plots of true mean pig weight versus estimated mean pig weight of grower (Figure 6.3) and finisher batches (Figure 6.4) are shown for each purposively selected sample. Table 6.3 shows the sampling error for each purposively selected sample stratified by production stage. Sampling errors were smaller when selecting pens by their weight rank compared to random selection of pens. Selection of grower pens by pen location yielded inconsistent results.

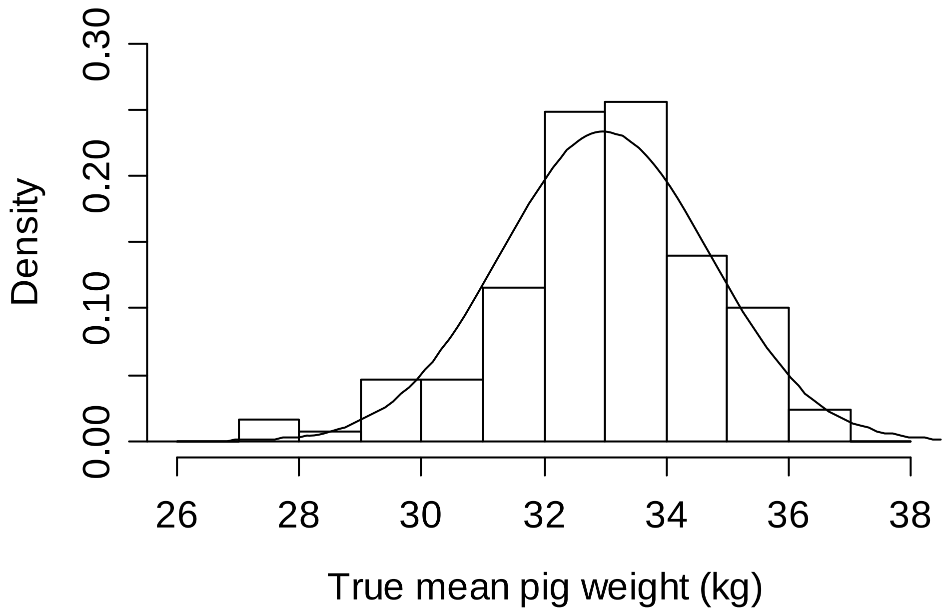

Figure 6.1. Frequency distribution with superimposed normal distribution of true mean pig weight of 129 individual batches of grower pigs weaned between December 2001 and June 2004. True mean pig weight was derived using data from eight pens per batch.

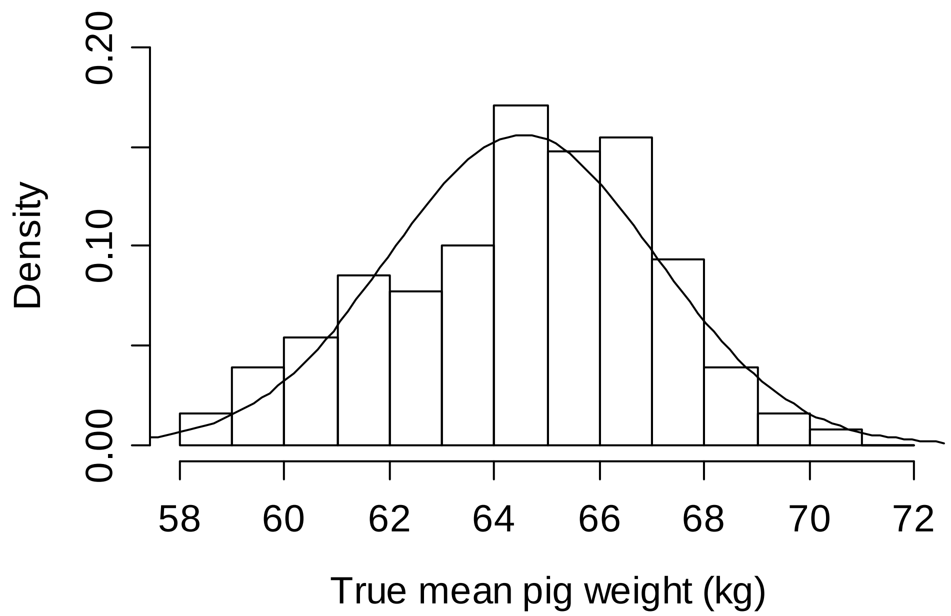

Figure 6.2. Frequency distribution with superimposed normal distribution of true mean pig weight of 129 individual batches of finisher pigs weaned between December 2001 and June 2004. For finisher batches with more than eight pens, true mean pig weight was derived using data from eight randomly selected pens.

Table 6.2. ANOVA results for the effect of finisher shed on coefficient of variation in mean pig weight of pens within a batch of 129 batches of finisher pigs. Finisher batches were housed in shed A (n = 18), shed B (n = 37), or sheds C and D (n = 74).

Source	Degree of Freedom	Sum of Squares	Mean square	F-ratio	P-value
Between samples	2	0.09	0.05	1.75	0.18
Within samples	126	3.34	0.03		
Totals	128	3.43			

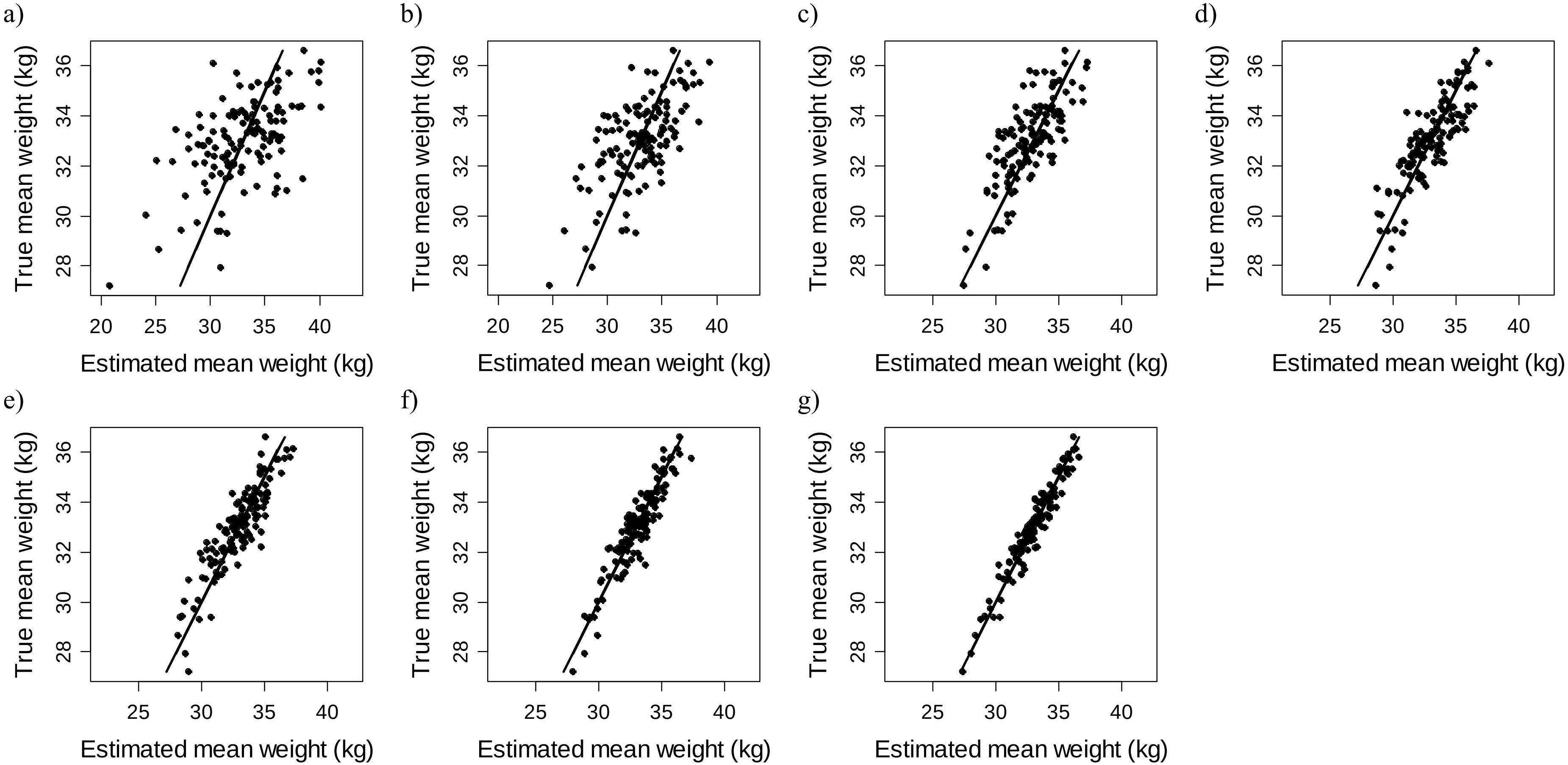

Figure 6.3. Scatter plots of true mean pig weight versus estimated mean pig weight following random sampling of a) 13%, b) 25%, c) 38%, d) 50%, e) 63%, f) 75%, and g) 88% of eight grower pens. Data were derived from 129 batches of pigs. Line represents perfect fit.

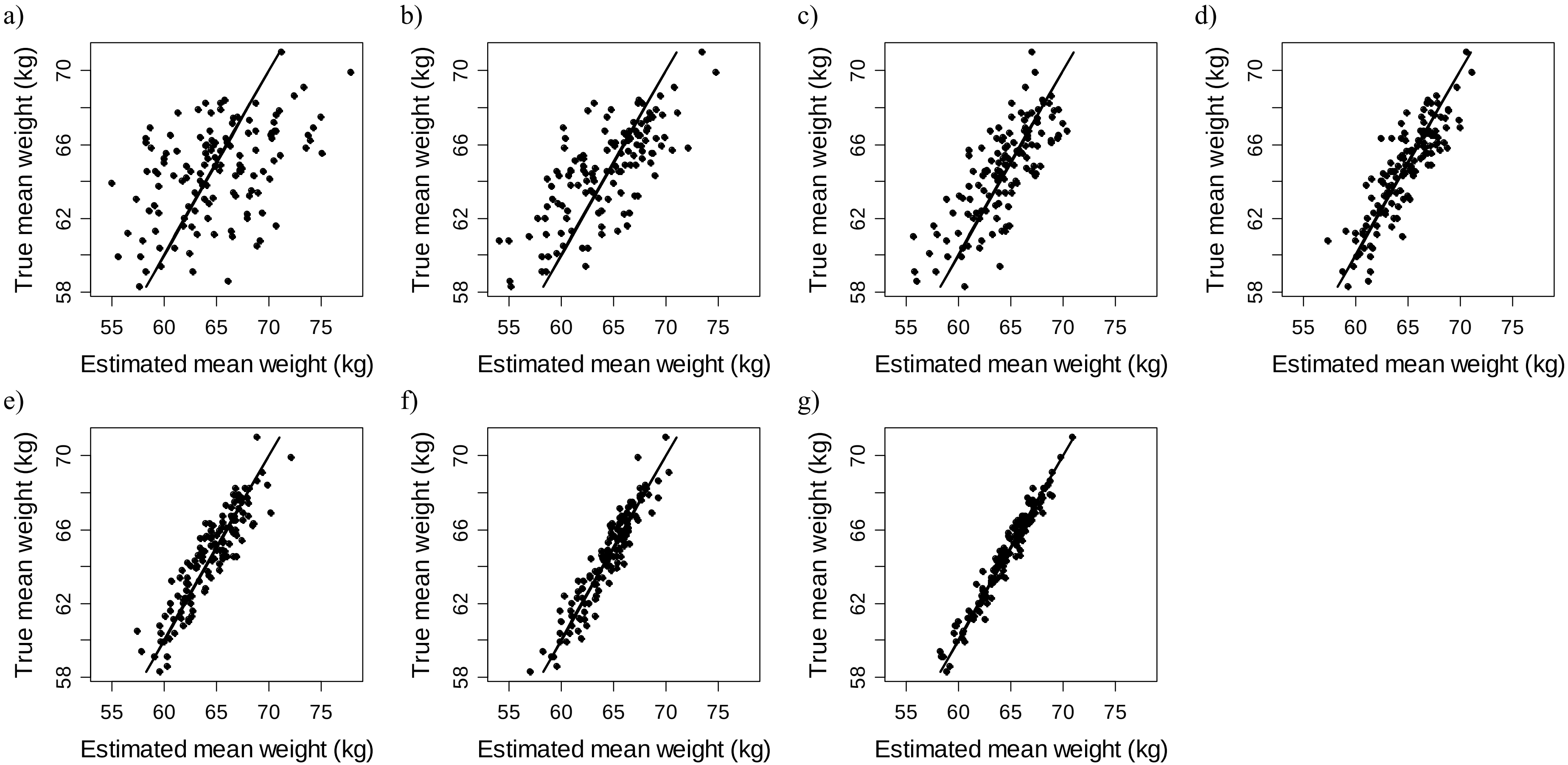

Figure 6.4. Scatter plots of true mean pig weight versus estimated mean pig weight following random sampling of a) 13%, b) 25%, c) 38%, d) 50%, e) 63%, f) 75%, and g) 88% of eight finisher pens. Data were derived from 129 batches of pigs. Line represents perfect fit.

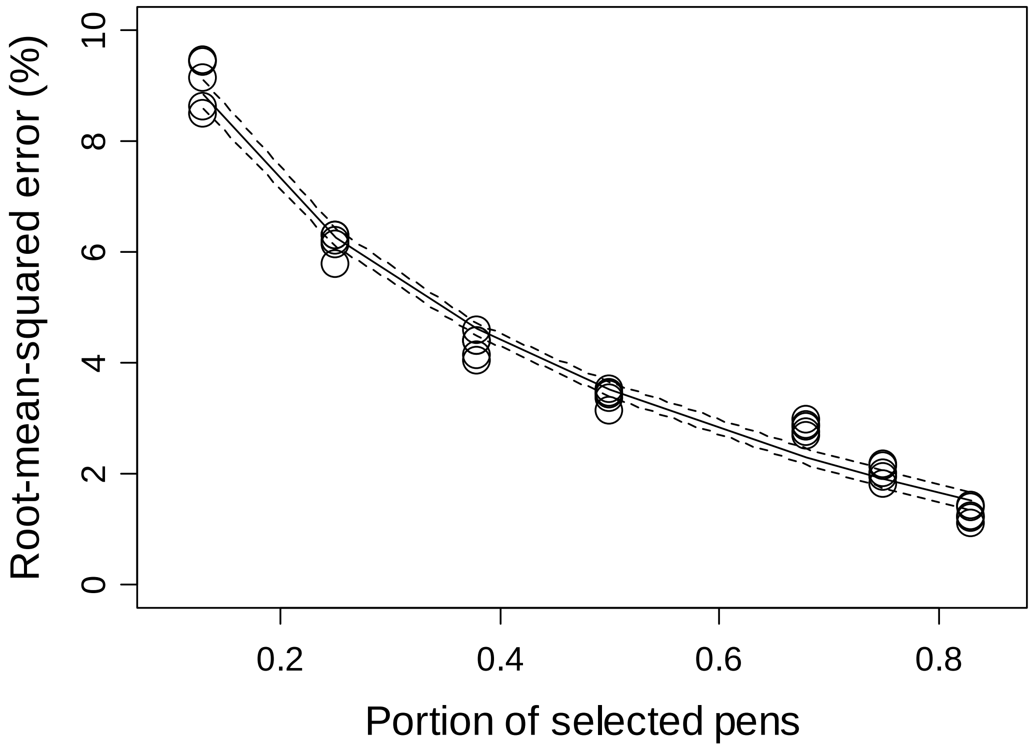

Figure 6.5**.** Change in sampling error when increasing the portion of selected pens derived from five repetitions of random sampling. Pens were selected from eight pens of each of 129 batches of grower pigs. The mean sampling error of all batches is expressed as the root-mean-squared error in percent of the mean of mean pig weight of all batches. A logarithmic regression line and its 95% prediction interval (dashed lines) were fitted.

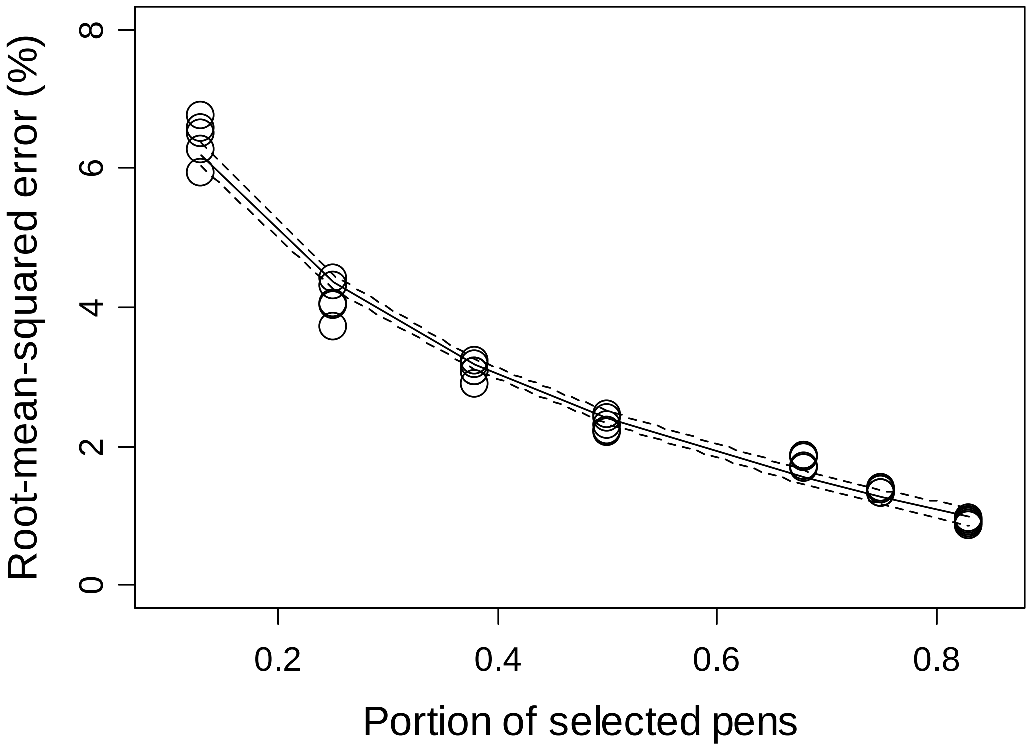

Figure 6.6. Change in sampling error when increasing the portion of selected pens derived from five repetitions of random sampling. Pens were selected from eight pens of each of 129 batches of finisher pigs. The mean sampling error of all batches is expressed as the root-mean-squared error in percent of the mean of mean pig weight of all batches. A logarithmic regression line and its 95% prediction interval (dashed lines) were fitted.

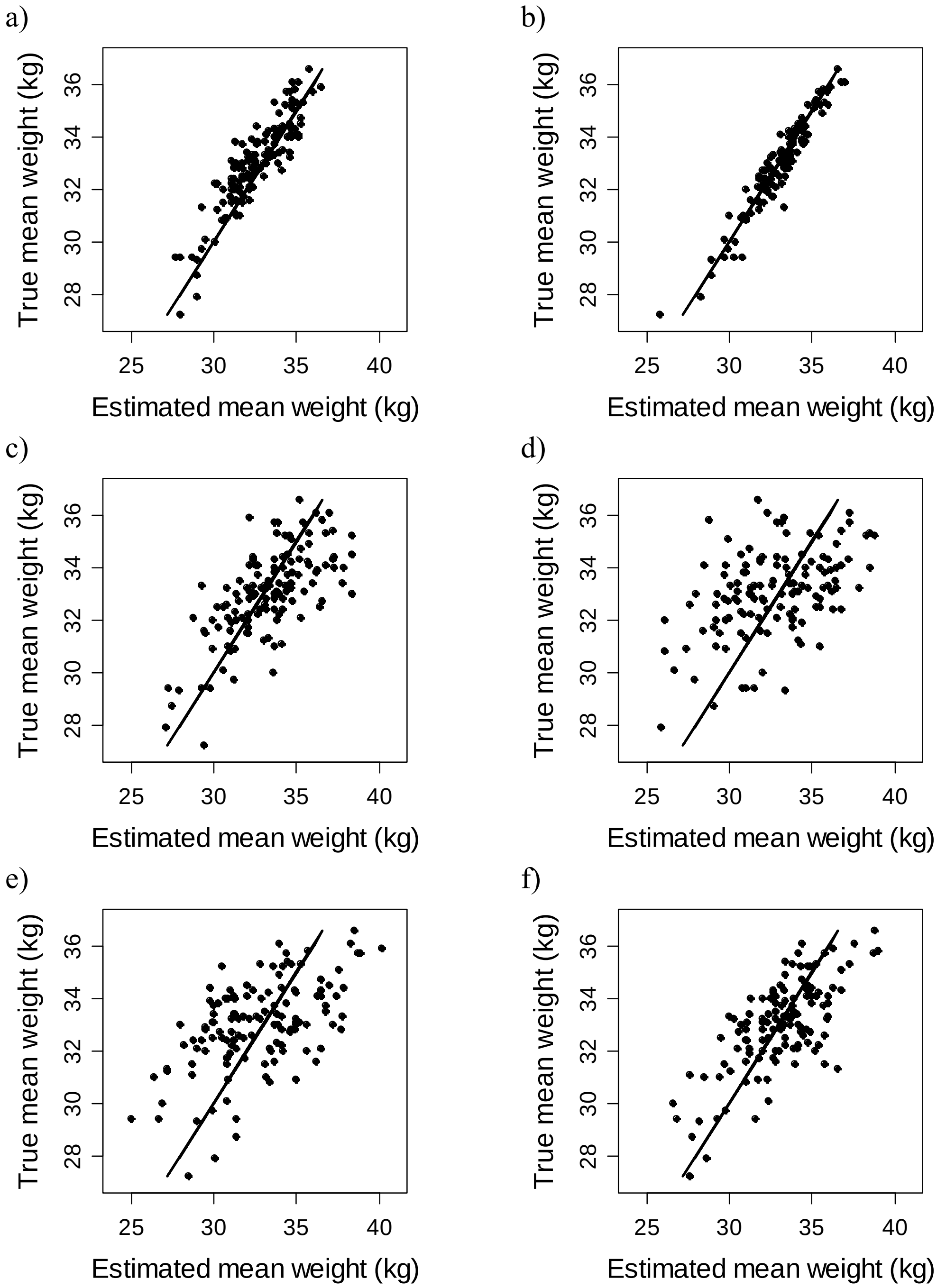

Figure 6.7. Scatter plots of true mean pig weight versus estimated mean pig weight of 129 batches of grower pigs following purposive sampling of two out of eight pens. Pens were selected a) with the lowest and highest weight rank, b) with the third and fourth highest weight rank, c) from pen locations 3 and 6, d) from pen locations 1 and 5, e) from pen locations 2 and 4, and f) from pen locations 7 and 8. Line represents perfect fit.

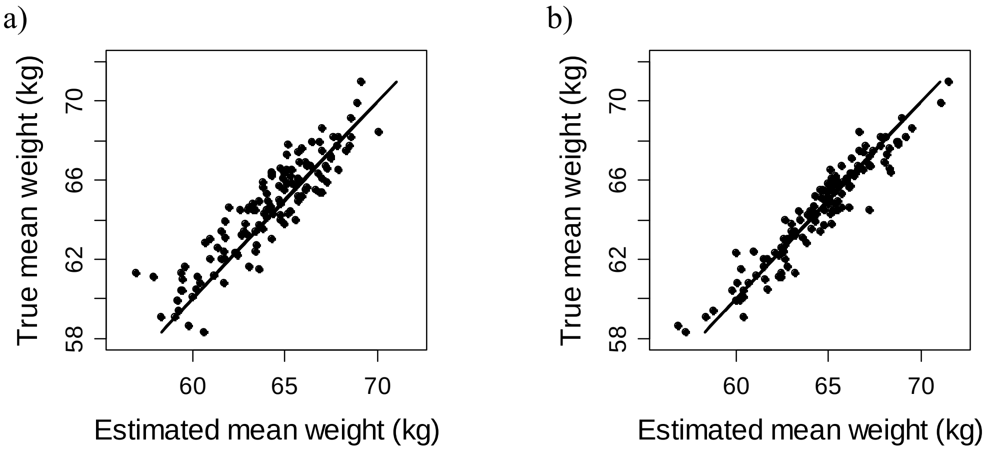

Figure 6.8. Scatter plots of true mean pig weight versus estimated mean pig weight of 129 batches of finisher pigs following purposive sampling of two out of eight pens. Pens were selected a) with the lowest and highest weight rank and b) with the third and fourth highest weight rank. Line represents perfect fit.

Table 6.3. Estimated sampling error following purposive sampling of two pens per batch. Data were generated from 129 batches of grower and finisher pigs. The sampling error is expressed as the root-mean-squared error (RMSE) in percent of the mean of mean pig weight of all batches. Pairs of pen locations had been randomly selected.

Production stage	Sampling strategy	RMSE (%)
Grower		
	Pens with lowest and highest weight rank	2.2
	Pens with fourth and fifth highest weight rank	1.2
	Pen locations 3 and 6	4.3
	Pen locations 1 and 5	6.9
	Pen locations 2 and 4	6.6
	Pen locations 7 and 8	4.1
Finisher		
	Pens with lowest and highest weight rank	1.5
	Pens with fourth and fifth highest weight rank	1.0

6.4 Discussion

Sampling was simulated using retrospective pen weight data of one New Zealand pig farm. Therefore, results may not be applicable to other farms. First, results derived from one farm are not sufficient to draw inferences to other farms. Secondly, retrospective data might be biased since potential confounders such as changes in sorting and data collection could not be controlled. However, long-term changes were expected to be small since it was a small farm with good management and no changes in farm staff throughout the studied period.

Sampling errors in the current data set are sensitive to changes in between-pen variation, which was expressed as the coefficient of variation in mean pig weight between pens of batch i (CV_i). Sorting pigs by size alters between-pen variation. The studied farm applied two methods of sorting throughout production. At weaning, pigs were sized to match pen mates, whilst at subsequent transfers the smallest pigs from each pen were mixed to create new pens. The former method is likely to increase between-pen variation compared to not sorting pigs as it increases the deviation from the overall mean for pens with relatively light and heavy pigs. In contrast, the effect of removing the lightest pigs from each pen on between-pen variation is less clear. However, it can be assumed that both sorting strategies alter the shape of the distribution of mean pig weights of pens within a batch. Therefore, sampling errors in this study, particularly those relating to purposive sampling of weight ranked pens, may not be applicable to those farms that do not sort by weight.

Two sources of bias with potential effects on CV_i were investigated. First, it was assessed whether CV_i changed over time. The lack of a linear long-term trend suggests that the farm sorted in a consistent manner throughout the study period. Secondly, differences in housing capacities of finisher sheds caused the number of finisher pens to range from eight to ten pens, which may have biased between-pen variation. However, no significant differences in the between-pen variation for batches housed in different finisher sheds were observed. Therefore, differences in the housing capacities of different finisher sheds were not likely to be a major source of bias.

A consistent number of eight pens per batch was chosen to allow direct comparisons of sample sizes and thus sampling errors across batches and production stages. This resulted in the exclusion of 14.7% of finisher pens, which may have led to selection bias. This bias is likely to be small as pens were randomly excluded, and exclusions did not significantly alter either mean pig weight of individual batches or CV_i.

Sampling error was assessed directly by calculating the root-mean-squared error (RMSE) between true mean pig weight (μ) and estimated mean pig weight of selected pens ($\bar{y}$). Using the RMSE was considered appropriate as the true population mean, i.e. the mean pig weight of pigs in all eight pens of a batch, was known and could be regarded as an unbiased estimate. The RMSE's were expressed as a percentage of mean pig weight of all batches, as it allowed direct comparisons of RMSE's between production stages. The R-squared value could have been chosen as a measure of how much variance in μ was explained by $\bar{y}$. However, the R-squared value represents a relative measure and as such does not provide an estimate of the actual magnitude of the sampling error (Legates and McCabe, 1999). Therefore, RMSE was considered the more relevant statistical measure.

It would have been interesting to compare observed random sampling errors with theoretical sampling errors, which can be derived from the sample variance (Tryfos, 1996; Thompson, 2002). This would have allowed verification of the obtained estimates. However, reasonable estimates of sampling variation based on the standard error of the sample can only be calculated when the sample size exceeds 30. The small sample size of pens in the present data set would not have produced meaningful variance estimates. Therefore, the decision was made not to make comparisons between the observed sampling error and the theoretical sampling errors.

Between-pen variation was greater for grower (CV_i = 9.7%) than finisher batches (CV_i = 6.6%). This could be due to a number of factors including removal of the smallest pigs from each pen at transfer to the finisher stage. Alternatively, the difference in CV_i may reflect a true reduction in between-pen variation between the two production stages. The latter is supported by Payne *et al.* (1999) who proposed values for coefficients of variation in pig weight within a batch based on experience from research and commercial facilities. According to Payne, estimates of the CV for pigs weighing 20 to 25 kg were 15% to 18%, while the CV for market weight pigs was 10%.

One to seven pens were randomly selected to simulate the entire range of possible sample sizes, and the process was repeated five times to allow the calculation of prediction intervals for the fitted regression line. Analysis showed that estimated mean pig weight gradually approximated the "truth" when increasing the portion of selected pens. Whilst increasing the portion of randomly selected pens is effective in reducing the sampling error, there is a diminishing return to the increased time and cost. The similar shape of the logarithmic response curves of the grower and finisher data suggests a truthful representation of the diminishing return relationship between weighing intensity and sampling error. This diminishing return relationship was expected, as theoretical estimates of sampling errors decrease proportionally by the square root of sample size (Tryfos, 1996; De Veaux, 2008). Sampling errors for randomly selecting two pens were 6.2% for grower and 4.4% for finisher batches. The slightly higher sampling errors of grower compared to finisher batches could be due to a number of factors, the most likely one is the greater between-pen variability of grower batches.

Compared to random selection of two pens, purposive selection of pens with the lowest and highest weight rank reduced sampling error by 65% for grower and 66% for finisher batches. Similarly, selecting pens with the fourth and fifth highest weight rank reduced sampling error by 81% and 77% for grower and finisher batches, respectively. The greater homogeneity of the sample when consistently choosing the same weight rank may explain the observed reduction in sampling error. In contrast, purposive sampling of grower pens by their pen location provided inconsistent results compared to sampling errors when selecting two pens at random.

These results suggest that purposive sampling of weight ranked pens leads to a considerable reduction in weighing effort. Several factors may have contributed to these results. First, purposive selection of pens was undertaken using an existing data set. Thus, the desired selection criteria were consistently met. However, on a farm, the weight rank of pens is unknown, and producers would have to guess the weight rank of pens at each weighing. Failure in consistently determining the desired weight rank correctly would result in systematic errors (i.e. sampling bias). The presence of sampling bias could substantially reduce the internal validity of the data collected on the farm, and inferences about the study population could not be considered true.

Besides the risk of not meeting desired selection criteria, the distribution of mean pig weights of pens within a batch represents another source of bias. This would be a substantial problem if estimated mean pig weights were calculated using the pens with the lightest and heaviest weight rank. Taking the mean of the extremes of a distribution only reflects the true mean if the underlying distribution is approximately normal. In contrast, if the distribution of pig weights in a batch was skewed the mean is an inappropriate descriptor of central tendency thus producing biased estimates. Both the accuracy of producers in determining the desired weight rank of pens and the distribution of mean pig weights of pens within a batch cannot be estimated without weighing all the pigs in the batch. Based on these considerations, the author does not recommended purposive selection of pens with the lightest and heaviest weight rank or by their pen location, as both these sampling methods may introduce bias.

Producers who wish to use purposive selection of representative pens are advised to determine, how accurately they are able to identify representative pens. This may be achieved by guessing the weight rank prior to weighing all pens for at least ten weeks. The correct determination of the desired weight rank of pens would be facilitated if between-pen variation is large and/or within-pen variation is small. Both an increase in between-pen variation and a reduction in within-pen variation could be achieved if pigs were sorted by size. Sorting pigs by size is a management strategy to try to reduce variation within pens. Several authors have shown that the initial reduction in within-pen variation after sorting diminishes over time resulting in similar within-pen variation compared to unsorted pigs (O'Quinn et al., 2001; Wolter et al., 2002). This is particularly the case if pigs are kept in a competitive feeding environment (Georgsson and Svendsen, 2002).

Therefore, the weight rank of pens within a batch is likely to change over time. Hence, if the same pens are followed over time, they may not remain representative throughout production. This may result in biased weight estimates at later production stages.

Given these considerations, the author recommends to select pens at random. Random sampling eliminates sampling bias (Carlson, 1997), and thus reduces the sampling error to sampling variation. The lack of sampling bias allows a producer to draw truthful inferences about the performance in a grower batch. Furthermore, as sampling variation is predictable, it can be considered when making decisions based on data collected using random sampling. Finally, if a producer is concerned about sampling variation they can reduce it by increasing sample size.

The choice of how many pens should be randomly selected is largely a matter of economics. Presented results may be used to balance the accuracy of sample weights against the costs of data collection. Producers can determine how much accuracy is worth to them by answering the following questions (Polson et al., 1998): 1.) What do I want to learn from the information I am collecting? 2.) What type of decisions do I want to make based on this information? Producers can then use the presented results as an indication of what portion of pens needs to be sampled following random sampling. Weighing half the batch should provide a good estimate of overall batch performance whilst still providing a considerable reduction in weighing effort compared to weighing the entire batch. This recommendation was based on the relative reduction in sampling error being less than 1% at both production stages if at least half of the batch was weighed.

These recommendations differ from guidelines given by commercial software packages. Porkma$ter's recommendation to weigh at least two representative pens should be considered with caution due to the reasons outlined above. Furthermore, both PigWIN and Porkma$ter provide a fixed number (20 pigs and two pens, respectively) as a recommendation of sample size. However, a fixed sample size does not account for differences in population size, which is particularly important if population size is small. Instead, recommendations of sample size should be based on a portion of the population.

In conclusion, while the results support purposive sampling of weight ranked pens, it is not recommended due to the unquantifiable risk of obtaining biased estimates. Rather, the author supports the use of random sampling to select pens. If pens are selected at random, presented results may serve as a tool to guide decision makers in their quest to balance time and cost factors against the accuracy of sample weights. It is recommended to weigh half the batch following random sampling to obtain reliable estimates of overall batch performance.

Chapter 7 General discussion

7.1 Introduction

This thesis has investigated sources of errors in pig weight measurements and methods that could be used to reduce these errors. It was conjectured that a better understanding of errors in pig weights may increase the efficiency of performance monitoring in the growing herd. In this final chapter, the research approach and results of this thesis are critically reviewed to assess the extent to which theses objectives have been reached. It follows a discussion of practical implications of the results and recommendations for future research.

7.2 Limitations of the thesis

A weakness of this thesis was that all studies were conducted on one commercial pig farm in the North Island, New Zealand. It is recognized that this farm may not be truly representative of commercial herds in New Zealand, since conditions found on this farm may be different in various ways from those on other farms. Therefore, the magnitude of errors reported in this thesis may not be applicable to other farms. However, results regarding diurnal weight changes and the effect of different sampling strategies on sampling error are in agreement with published literature and consistent with field experience, which adds to confidence about their likely validity. Therefore, these results can be used to increase producers' awareness of sources of errors in weight records. Chapter 5 also provides what is believed to be the first study showing the effect of feed withdrawal on variability in live weight and growth rate of pigs. Since these results were only derived from one farm, the effect of feed withdrawal should be repeated on other farms. Furthermore, the effect of feed withdrawal on long-term pig performance should be investigated.

7.3 Sources of errors in pig weights and methods to reduce these errors

7.3.1 Measurement error due to biological factors

Chapter 4 and Chapter 5 investigated two different methods to reduce variability in live weight records: i) standardization of weighing time and ii) feed withdrawal. Both are methods which have been recommended to reduce error in weight measurements due to fluctuations in gut fill (Lawrence, 2002; Scanes, 2003). However, to the author's knowledge, a precise estimation and validation of the effect of time of day and feed withdrawal on pig weight measurements has not been published. Gut fill may comprise approximately 5% to 10% of live weight depending on the feeding system and the time elapsed since the last feeding activity occurred (Stranks et al., 1988; Kyriazakis and Whittemore, 2006).

Chapter 4 investigated the effect of time of day on live weight of finisher pigs fed either ad libitum or via a computerized liquid feeding system using descriptive plots and multivariate repeated measures analysis. Descriptive plots indicated little variation in the coefficient of variation in live weight over time for either feeding system. In contrast, mean weight changed with time of day, and these changes appeared to be associated with feed intake patterns. However, the effect of time of day on pig weight varied across days for both feeding systems as indicated by significant interactions in the multivariate model.

Results provided an indirect indication that variability in gut fill represents a source of error in live weight measurements. Hence, it was concluded that standardizing weighing time is important to reduce fluctuations in mean pig weight. However, the interaction between day and time of day suggests that diurnal fluctuations in live weight are not consistent between days, particularly in ad libitum fed pigs. It was hypothesized that meal feeding may have had a standardizing effect on feeding behaviour and thus gut fill of pigs fed via the computerized liquid feeding system. Feed intake patterns and thus gut fill changes are likely to be more variable under ad libitum compared to meal feeding. It was concluded that standardization of weighing time appears insufficient to eliminate variability in pig weights due to gut fill, particularly if pigs are fed ad libitum.

One limitation of Chapter 4 was that the actual act of weighing pigs may have altered feeding behaviour, and this may have affected live weight changes. This bias could have been reduced by using automatic weigh stations, which eliminate the need to handle pigs. However, automatic weigh stations were not available on the study farm. As another lower cost option, the experiment could have included an adaptation period allowing pigs to become familiar with the handling procedure. However, pigs in the study of Augspurger and Ellis (2002), which provided the evidence that manual weighing may affect feeding behaviour, were already familiar with regular handling and weighing before the start of the experiment. Furthermore, Augspurger stated that pigs were easy to handle and walked directly onto scales with little human interaction needed. Therefore, including an adaptation period to familiarize pigs with the weighing procedure may not have been effective in avoiding potential bias associated with the act of weighing pigs manually. It was concluded that manual weight measurements may have biased the magnitude of weight changes, but were unlikely to have had a major effect on feed intake patterns. Therefore, results may be used as an educational tool to illustrate that weighing time is important when assessing pig weights.

Results from Chapter 4 showed that standardizing weighing time is effective in reducing errors in pig weights due to biological factors such as gut fill. However, the significant interaction between time of day and day indicated that the effect of time of day on pig weight was not consistent between days. The aim of Chapter 5 was to assess whether between-pig variation in live weight could be reduced by a period of overnight feed withdrawal. The experiment included a control group to verify that the effect on between-pig variation was attributable to the effect of treatment.

For grower and finisher pigs, feed withdrawal was associated with a significant reduction in variability in live weight by 4.0% to 11.1% and in growth rate by 11.3% to 11.5%. In contrast, variability in live weight and growth rate was similar in control pigs at the end compared to the start of each experimental period. This suggests that reduced variability in weight records of unfed pigs was due to the effect of feed withdrawal. Other authors did not detect a reduction in carcass weight after 18 to 20 hours feed withdrawal (Warriss and Brown, 1983; Beattie et al., 2002; Bidner et al., 2004). Hence, it was hypothesized that the observed reduction in variability was predominantly associated with losses of gut fill.

Feed withdrawal was not recommended for weaner pigs due to three reasons. First, feed withdrawal may pose a higher health risk on weaner pigs due to their small gut capacity and their immature immune system. Secondly, variability in gut fill is likely to produce relatively small errors in weights of weaner pigs due to their small gut capacity. Thirdly, results showed that feed withdrawal was not consistently associated with a significant reduction in variability in live weight and average daily gain in weaner pigs. Although it is recognized that the six-hour shorter feed withdrawal period in weaner compared to grower and finisher pigs may have been insufficient to induce a significant effect, the gain from withdrawing feed for longer is not expected to outweigh potential health risks in weaner pigs.

The study could have been improved by following pigs over time up to the point of slaughter to assess whether feed withdrawal may induce long-term negative effects on pig performance or morbidity. However, since pigs in this experiment were not truly allocated to treatment groups at random, statistical comparisons between treatment groups would have been invalid. Hence, further studies are required to repeat the observed effect, and to assess whether feed withdrawal may have a negative impact on growth performance.

In conclusion, results support that standardization of weighing time is effective in reducing diurnal variation in pig weights. For grower and finisher pigs, a further reduction in errors of pig weights and average daily gain may be achieved by withdrawing feed prior to weight measurements. However, it needs to be further investigated whether feed withdrawal may have negative effects on long-term performance and pig health.

7.3.2 Sampling error

Chapter 6 compared the magnitude of the sampling error between (1) different sample sizes following random sampling, and (2) random sampling and purposeful sampling when sampling two out of eight pens. Sampling was simulated using retrospective pen weight data. It was routine farm management to allocate pigs to pens by size at weaning, and to mix the smallest pigs from each pen to create new pens at the start of subsequent production stages. Hence, sampling errors in this study, particularly those relating to purposeful sampling of weight ranked pens, may not be applicable to those farms that do not sort by weight.

For random sampling, there was a diminishing return between increasing the proportion of pens selected and reduction in sampling error. The relationship between sample size and sampling error was best described by a logarithmic equation. Purposive selection of the pens with the lowest and highest weight rank or the two pens with the most average weight rank resulted in sampling error that were more than 64% lower than sampling errors for two randomly selected pens. However, in practise there is a considerable risk of introducing sampling bias when selecting pens by their weight rank. First, it is unknown whether pens are selected with the desired weight rank, unless all pens of the batch are weighed. Secondly, the mean is an inappropriate descriptor of central tendency if the distribution of the mean pig weights of pens within a batch is not normal. Therefore, it is strongly recommended to apply random sampling, which eliminates the risk of sampling bias. It was suggested that weighing half the pens of a batch would provide a reasonable accuracy when the aim is to assess mean batch weight.

7.3.3 Summary

The studies described in this thesis evaluated two categories of errors in pig weights - measurement error due to variability in gut fill and sampling error. Both categories of errors can be described as random or systematic errors. Systematic errors affect the validity of measurements, whereas random errors reduce precision (Noordhuizen et al., 2001). Hence, systematic errors are of greater concern than random errors since it leads to distorted results and thus, possibly, misleading conclusions (Woodward, 2004). In contrast, random errors introduce variability in the data thus making interpretation of records more difficult.

Variability in gut fill may cause systematic errors in individual pig weights when pigs systematically differ in feed intake patterns, and thus gut fill. For instance, small pigs may consume more feed during the night than their heavier counterparts in a competitive ad libitum feeding situation. Variability in gut fill between individual pigs may be less of a concern when the aim is to assess mean pig weight of a group of pigs and weighing time is kept constant. Systematic errors associated with sampling can be eliminated by selecting pens or pigs at random. A further advantage of random sampling is that a reduction in random error can be achieved by increasing the sample size. Hence, random sampling produces sampling errors that are i) free of sampling bias and ii) more predictable than sampling errors derived from a purposeful sample.

Automatic weigh stations are increasingly used in research to assess pig weights as a means of non-invasive semi-continuous performance monitoring, and may gradually replace mechanical scales on commercial farms. Automatic weigh stations can take multiple weight measurements per day, which allows adjusting for random errors due to diurnal fluctuations in gut fill. However, weight measurements are less likely to be standardized by time of day. Hence, presented results may facilitate the interpretation of weight records derived from automated technologies. Furthermore, owing to the expense of automatic weigh stations, it may only be possible to install such technology in selected pens. Results from Chapter 6 may assist producers in their decision of which method to use to allocate pigs to these monitoring pens.

Common parameters calculated from pig weights are growth rate and feed efficiency. Calculation of growth rate and feed efficiency requires accurate estimates of pig counts, pig ages, and feed intake. Potential sources of errors in these latter parameters were addressed in the literature review. Similarly to pig weights, the division of errors into systematic and random is important, because these components have a different effect on the interpretability of growth rate and feed efficiency.

7.4 Practical implications

This thesis has investigated sources of errors and methods that could be used to reduce these errors. The presented work leads to following conclusions:

- Time of day should be kept consistent when pigs are weighed.
- Withdrawing feed for approximately 17 hours prior to obtaining weight measurements may offer benefits in reducing between-pig variability in pig weights and growth rate. The reduction in between-pig variability is likely to be attributable to standardization of gut fill between animals.

- A sample of pens or pigs should be selected from a batch using random sampling. Weighing half the batch should provide reliable estimates of overall batch performance.

A better understanding of sources of errors may benefit both pig producers and consultants such as pig veterinarians. Pig producers may utilize this information to reduce errors in pig weights and growth rate. Enhancing the accuracy of pig weights makes collected records more meaningful, thus increasing the interpretability of records. Furthermore, the thesis has produced meaningful figures illustrating the effect of time of day and sample size on variability in pig weights. This information may be useful when illustrating the effect of time of day and sample size to people involved in data collection.

Pig veterinarians have increasingly recognized the potential of extending their service to supporting overall production and economic decisions (e.g. choice of genetics, modification of pig flow, marketing decisions). Traditionally, pig veterinarians used production data for identification of disease problems. In comparison to disease detection, production and economic decisions are concerned with smaller changes in production parameters. Therefore, pig veterinarians need to be aware of sources of errors in production parameters and methods how to reduce these errors to improve their ability as consultants.

7.5 Recommendations for further research

Monitoring growing herd performance appears to be underutilized on commercial farms. It was conjectured that a better understanding of sources of errors in pig weights might improve interpretability of records in the growing pig herd, thus contributing to an increased adoption of growing herd monitoring. However, other factors than erroneous measurements are likely to impede the application of an effective monitoring system in the growing herd. Four areas are recommended where research could contribute to a wider use of monitoring systems.

First, it is important to evaluate, which factors impede the successful application of monitoring systems in commercial growing pig herds. Questionnaire surveys of pig producers, consultants, software developers, and other experts could be conducted to identify problems experienced with monitoring systems in the growing herd. Based on such knowledge, assistance in establishing a monitoring system could specifically address these problem areas.

Secondly, research is required to gain an improved understanding of the interrelationship between factors affecting pig performance and farm profitability on commercial farms. Simulation modelling may be useful in identifying the most sensitive performance parameters under various farm and external conditions. Furthermore, simulation models may help developing clearer guidelines of how to utilize information from collected data more effectively to enhance financial returns.

Thirdly, decision-makers would benefit from an improved knowledge regarding the cost-effectiveness of a monitoring system. Longitudinal studies could be used to assess the effect of implementing a monitoring system by comparing farms using such a system with farms not using it. Selection bias may occur if farms are included with an existing monitoring system, as these farms may systematically differ from farms not using a monitoring system (Tomaszewski et al., 2000). Applying a cohort design, thus only including farms that have not used a growing herd monitoring system previously, avoids potential selection bias associated with the uptake of a monitoring system. The disadvantage of cohort studies is that they are expensive and take a long time to complete. Therefore, descriptive studies such as case reports may provide preliminary quantitative data for decision-makers. Financial returns associated with the implementation of a monitoring system should account for costs of data collection, data interpretation, and software use.

Lastly, psychological research could be used to characterise farmers' decision-making process and evaluate decision outcomes. Knowing and understanding why people do what they do is likely to help transforming collected data to useful information and making effective decisions. For instance, Fountas *et al.* (2006) presented a model describing the interrelationships between decision-analysis factors, decision triggers, and information needs and flows on crop farms. Twenty-one decision-analysis factors characterised a farm manager’s decision-making process. These factors were incorporated in a decision flow diagram, which was flexible enough to fit the different operations and helped managers to structure their decision-making approach. Although following systematic decision-making steps may not lead to perfect decisions, it could help decision-makers to approach problems in a systematic and structured manner.

Outcomes from the research areas outlined above may allow developing a more structured approach to growing herd monitoring and decision-making. However, effective communication of research outputs is critical to support decision-makers in the design and development of a monitoring system. Presenting results at pig conferences, allows reaching producers and consultants with a strong interest in production and profit optimization. Another approach to communicate results to decision-makers is the development of effective training packages designed to provide a more structured approach to monitoring. Moreover, such training packages could be incorporated in software packages for the growing pig herd. For instance, Nuthall (2006) suggested that computerized packages could include well-constructed educational games stimulating interests and helping understand interactions on farms. The successful solution of a series of these games may even include an educational certificate. This interactive approach may further contribute to an improved understanding of the software itself.

7.6 Conclusion

This thesis has yielded readily applicable recommendations to improve accuracy of pig weight records on commercial pig farms. The thesis addressed two sources of errors that is the error due to variability in gut fill and sampling error. For both sources of error, the potential introduction of random and systematic errors was discussed. Systematic errors should be avoided as much as possible, as they affect the validity of records. In contrast, minimizing random errors reduces the noise in the data, thus facilitating data interpretation and decision-making. This knowledge may contribute to a better use of pig weight records in the growing pig herd.

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