Piglet birth weight uniformity as a predictor of future performance

by

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Declaration

I, Samantha van der Westhuizen, declare that the dissertation, which I hereby submit for the degree Msc (Agric) Livestock Production and Ecology at the University of Pretoria, is my own work and has not been submitted by me for a degree at this or any other tertiary institution.

SIGNATURE:

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Abstract

The pig industry is an important and growing economic sector in South Africa and improvement in efficiency is vital. Reproductive traits have become more important as it has been realised that these entail the main source of profit, with the production of many viable offspring. As the focus on increasing litter size has amplified, there has been a concurrent decrease in within-litter birth weight uniformity. A decrease in uniformity has been linked to a decrease in piglet health and welfare, performance, and an increase in management requirements and costs. The purpose of this study was to investigate the merit of including within-litter birth weight uniformity in the breeding objective. An on-farm trial was conducted, that included 40 Duroc, 39 Landrace, and 40 Large White dams. Data was recorded for their first three parities to measure piglet performance, taking into account various effects. Piglet performance was measured using litter traits including number born alive (NBA), individual birth weight (BiW), 21 day weight (21W), weaning weight (28W), and 70 day weight (70W), as well as within-litter birth weight variation (CVB) and survival to weaning (SURV). A general linear model (GLM) was conducted to test the significance of piglet sex, dam breed, sire breed, season and year of birth, farrowing room, weaning room, fostering status (NAT/UNNAT), and the interaction of dam breed with sire breed, as effects. Sire breed and season and year of birth was found to affect NBA in all parities ($p < 0.05$), CVB was consistently affected by dam breed ($p < 0.05$), and SURV was affected by sire breed in all parities ($p < 0.05$). Most traits were affected by the interaction between dam and sire breed ($p < 0.05$). Parity affected NBA, BiW, CVB, 28W, and SURV ($p < 0.05$), and all these, except 28W, were affected by parity's interaction with parental breed ($p < 0.05$). CVB was highest in the Large White dams in the first two parities, and highest in the Duroc in the third ($p < 0.05$), and mostly increased with increasing parity. Moderate correlations were found between NBA and BiW, and between BiW and 28W, for all parities ($p < 0.05$), and correlations between CVB and other traits were low. Further investigation with a larger animal sample size, more parities, and in a more controlled farm environment, is recommended.

Contents

List of Abbreviations

21W	Individual piglet weight at 21 days/3 weeks
28W	Individual piglet weight at 28 days/weaning
70W	Individual piglet weight at 70 days/10 weeks
ADG	Average daily gain
BiW	Individual piglet weight at birth
CV	Coefficient of variation
CVB	Within- litter coefficient of variation of birth weight
D	Duroc
DAFF	Department of Agriculture, Forestry and Fisheries
GLM	General linear model
h^2	Heritability
ID	Identification
IUGR	Intra-uterine growth restriction
IGF	Insulin-like Growth Factor
L/LR	Landrace
LSM	Least square mean
N	Number
NAT	Piglet remained on natural dam
NBA	Number born alive
OUT	Piglet fostered out
P	Statistical probability
PBSSA	Pig Breeders Society of South Africa
R^2	Coefficient of determination
SA	South Africa
SAPPO	South African Pork Producers Organisation
SAS	Statistical Analysis System
SD	Standard deviation
SE	Standard error
SGA	Small for gestational age
SURV	Survival to weaning

TNB	Total number born
UNNAT	Piglets fostered out from their natural dam
USA	United States of America
USD	United States Department of Agriculture
W/LW	Large White

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Chapter 1: Introduction

1.1 Introduction to the South African pig industry

Domestication of the pig began approximately 9000 years ago in the Fertile Crescent and Far East, with marked genetic and morphological changes occurring in the pig ancestor, *Sus scrofa*, over a short period of time (Larson *et al*., 2010; Ramos-Onsis *et al*., 2014). The introduction of pigs into South Africa took place in 1652, when Jan van Riebeeck brought domestic pigs into the Cape of Good Hope, which grew into the current South African pig industry (Visser, 2004). Structured animal breeding and selection was first introduced in South Africa (SA) in the 19th century with the inauguration of the "Pig Testing Scheme of the Union of South Africa and the Federation of Rhodesia and Nyasaland." It was based on Danish principles, and was launched in 1956 (Visser, 2014). This system was replaced in 1970 by the Boar Performance Testing Scheme, and in 1973 the Gilt Performance Testing Scheme was added (Visser, 2014). The implementation of the Pig Testing Scheme of South Africa is widely considered one of the most fundamental events in the history of pig breeding on the African continent (Juventis, 2009).

The pork industry plays an important economic role in SA. Approximately 4,000 workers are employed on pig farms, while in the broader pig industry, including abattoirs, processing, feed mixing, construction, transport, and consultation services, another 6,000 jobs are offered (DAFF, 2017c). Pork contributes 2.1% to the primary agricultural sector in South Africa (DAFF, 2017c). The Foreign Agricultural Service GAIN Report (USDA, 2017a) states that pork production in South Africa has grown at 3.5% per annum for the past ten years, driven mainly by consumer demand. However, the annual increase in pigs slaughtered increased only by 2.2%, implying the slaughtering of heavier pigs (USDA, 2017a).

Pig production is in a period of general growth. Meat prices in SA are increasing, along with stable feed prices, resulting in a current profitability indicator 85% higher than a year ago (SAPPO, 2018). SA pig numbers in the past decade have decreased, but tonnage produced has increased, as has per capita consumption (DAFF, 2017b; 2018, SAPPO, Pers. Comm., info@sapork.com). Although pork is the dominant protein consumed globally, SA consumption is comparatively small, but is expected to continue its growth (PigProgress, 2014). SA is a net importer, and imports appear to be increasing, with the main sources being Germany, Spain, and Brazil (SAPPO, 2017; 2018, SAPPO, Pers. Comm., info@sapork.com). Spain's production is levelling off, and German production decreasing according to recent data (AHDB, 2017), while Brazilian production appears to be increasing (USDA, 2017b). SA also exports to countries, primarily to African countries such as Lesotho, Mozambique, and Namibia (2018, SAPPO, Pers. Comm., info@sapork.com).

In South Africa, genetic improvements are achieved by a few large genetic companies, through research, technology, and international collaboration (PIC, 2018a; Topigs, 2018a). SAPPO (2018, SAPPO, Pers. Comm., info@sapork.com) acknowledges six pig breeding companies in South Africa (SA), which are PIC RSA, Topigs SA, Alliance Genetics SA, Niemen Stud, Sweetwell Stud, and Leanside Pig Stud. South Africa has a limited number of nucleus herds for a variety of reasons. Genetic improvement largely takes place outside of SA in specialised nucleus herd facilities, and SA then makes use of these improvements, hence not many of these facilities are required here. To start a pig production operation requires immense capital, due to the technology needed for modern pig production to be successful and competitive (DAFF, 2013; PigProgress, 2014). The running of these facilities also requires large amounts of water and electricity. Additionally, in order to be a viable operation, at least 300 sows are required. Hence, there is a large financial barrier to new market entries. These facilities are also highly specialised, so it creates a significant barrier to market exit, dissuading farmers from entering the market (PigProgress, 2014). The pig industry is particularly susceptible to health and safety issues, as well as global conditions, along with being highly labour intensive (DAFF, 2013). All these factors lead to a small and relatively isolated industry.

An outbreak of Listeriosis occurred in SA in early 2017, with 978 laboratory-confirmed cases between January 2017 and March 2018, and 183 human fatalities. The strain was traced back to “polony” and the processing environment thereof (WHO, 2018). Despite Listeriosis never having been found in pork, the consumers’ association of pork with processed products led to an industry crisis (SAPPO, 2018). After many campaigns to reduce the damage to the industry, the CEO of SAPPO reported that May 2017 saw an increase in the demand for fresh pork products, as well as a slight increase in processed product demand (NAHF, 2018).

The improvement in meat production in SA, as discussed above, is largely a result of improved genetics, housing, nutrition, health, technology, management, and information systems (Visser *et al*., 2014). This study will be focusing on reproductive efficiency, with special reference to breeding more uniform piglets in terms of birth weight. The study was requested by the South African Pork Producers’ Association (SAPPO). In order to meet the demands of the industry, pig producers have an aggregate goal made up of three focus points. The first is reproductive efficiency, which involves the production of as many healthy, uniform, and viable piglets as possible. The second is production efficiency, which includes growth efficiency, feed efficiency, and output efficiency. The third point is consumer satisfaction (Visser, 2014). Reproductive failure still accounts for 33% of sow culls within a herd (Rempel *et al*., 2015), and birth weight variation was chosen as a possible means of improvement due to its effect on piglet performance and its links with various maternal performance factors.

1.2 Aim

The aim of this study was to investigate piglet birth weight uniformity as a predictor of future performance. This aim will be achieved by attaining the following objectives:

1. Recording of piglet birth weight and its uniformity within the litters of the Landrace, Large White, and Duroc pig breeds over the first three parities
2. Association of birth weight uniformity and piglet performance with parity, dam and sire breed, piglet sex, season and year (period) of birth, farrow room, and weaning room
3. Association of future performance (as measured by 21 day weight, weaning weight, survival to weaning, and 10 week weight) with birth weight uniformity
4. Evaluate the merit of including birth weight uniformity in the breeding objective for South African pig breeding

Chapter 2: Literature Review

In the pig industry, emphasis has historically been placed on the improvement of growth traits and carcass quality. This resulted in significant increases in growth, and decreases in backfat thickness over the past century, but improvement in reproductive efficiency was largely neglected, with limited gains (Rothschild & Ruvinsky, 2011; Merks *et al*., 2012; Rutherford *et al*., 2013). More recently, reproductive traits have been highlighted. Litter size, and the performance of the litter received research focus, primarily due to increased slaughter animals per sow, maximising profit as well as decreasing cost, labour and environmental impact per kilogram production. Litter size has been of major interest as a reproductive trait, and has since been focused on and improved through improving management and effective implementation of genetic selection (Rutherford *et al*., 2013). This chapter will review relevant literature on the genetic improvement of pig fertility and production. The focus will be on female reproductive traits, particularly piglet birth weight uniformity as a possible trait for selection to advance the South African pig industry.

2.1. Breeding structure in the pig industry

The pig production industry is typically a three-tier system (pyramid), made up of the nucleus herds (master studs) which generate genetic changes, as depicted in Fig 2.1. The genetic pyramid, developed in the UK in the 1960’s, is applied to attain breeding objectives in the pig breeding farm. This is followed by the multiplier herds, and the commercial herds from which the slaughter progeny are produced (Rothschild & Ruvinsky, 2011; Visser, 2014). In South Africa, it is common for multiple tiers to be owned and run by a single entity, in order to decrease costs and increase control over quality (PigProgress, 2014). Performance testing and genetic selection takes place in the nucleus herd to optimise genetic progress and ensure that it is sustainable throughout the lower tiers, and should address the breeding objectives of the commercial breeders (Rothschild & Ruvinsky, 2011; Visser, 2014). This nucleus herd is specifically designed to maintain integrity of traits in purebred pig breeds and selection within these breeds for improvement and distribution throughout the production chain. This captures the benefits of heterosis, specifically by maintaining purebred maternal lines that create crossbred F1 maternal-line multiplier females (Knox, 2016). The nucleus breeders maintain specific breeds or breeding lines, including recognised breeds or their own synthetic lines (Rothschild & Ruvinsky, 2011). As an example, Juventis deals in purebred Landrace, Duroc, and Large White, while PIC RSA and Topigs Norsvin SA deal in purebred synthetic lines (Juventis, 2018; PIC, 2018b; Topigs, 2018b).

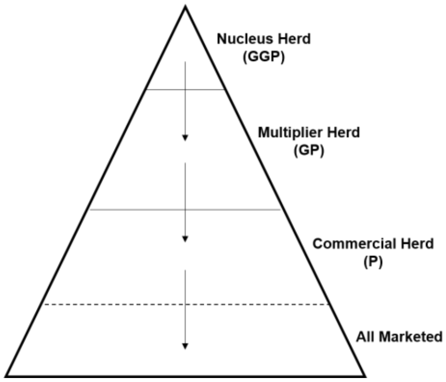

Figure 2.1 Genetic pyramid used in pig breeding systems (Adapted from ThePigSite, 2015)

The nucleus herds consist of purebred lines of swine, called the great-grandparent (GGP) stock, and they are kept isolated. These herds must maintain high genetic merit, exhibit hybrid vigour when crossed, and may consist of a variety of breeds to impart various characteristics to offspring. GGP are tested rigorously for carcass and meat quality, and growth and reproductive performance (Whittemore & Kyriazakis, 2006). From these, the grandparent (GP) stock are selected, some of which may replace the GGP stock. Some of these are used in multiplier herds to produce parent (P) stock, via crossbreeding, for sale to commercial herds. These commercial herds will produce the animals used for slaughter, via terminal sire crosses (Whittemore & Kyriazakis, 2006; Knox, 2011; Knox, 2016).

Crossbreeding is used to best meet the needs of the “end user.” The system uses breed complementarity, by taking two breeds with complementary biological types and breeding them to create a desirable animal. In pigs, this typically comes from crossing maternal traits (such as breeds with high fertility, mothering ability, etc.) with paternal traits (breeds with good meat quality, growth, carcass yield, etc.). The terminal-sire crosses, used in the lower tier, is where the offspring produced are desirable from a market standpoint, and are generally not kept for breeding. A common system is to cross a Landrace and Large White, and use female progeny to breed with a terminal sire, such as a Duroc (Bourdon, 2000; Whittemore & Kyriazakis, 2006; Rothschild & Ruvinsky, 2011; Visser, 2014). One of the most important reasons for crossbreeding is hybrid vigour, as it has particularly positive effects on traits with low heritability, like those involving fertility and survivability. These would be traits such as conception rate, litter size, and weaning rate. Maternal heterosis is particularly important, being the advantage of a crossbred dam over a purebred dam, which enhances litter traits such as piglet weight and litter size. The highest amount of hybrid vigour is obtained in the first crossed generation, hence these offspring are not often kept for further breeding (Bourdon, 2000; Whittemore & Kyriazakis, 2006; Rothschild & Ruvinsky, 2011; Visser, 2014).

Artificial insemination (AI) is the predominant method of breeding/mating in the genetic pyramid, and has been instrumental in global improvements of genetics, fertility, labour, and herd health. South Africa, itself, performs 70-75% of matings using AI (Krüger, 2015). The global AI revolution began in the 1990’s, with early development contributions (1926-1940) from Russia, USA, Japan, and Europe, and the establishment of the first artificial insemination centres in the 1980's (Knox, 2016). Boar semen cannot be cryopreserved due to low sperm survival, damage, and fertility issues, but is successfully preserved in liquid form, and a single ejaculate can be used to inseminate 10-20 females. The preservation of the semen particularly allows the use of high indexing sires on a multitude of farms without the need to transport or keep boars on site, and allows control over disease transmission (Knox, 2016). Using these breeding strategies and technologies, pigs can be bred according to the particular demands of the industry.

2.2 SA pig breeds

The most common pure breeds used in South Africa are the Large White, the Landrace, and the Duroc. These breeds are regularly used in crossbreeding systems, and will be discussed specifically due to their use in this study. The Large White pig breed (Figure 2.2) is originally from England, where it was formerly called the Yorkshire. It was recognised as a distinct breed in 1868, and imported to South Africa in the late 1890's. It has since become one of the leading pig breeds in the world (Whittemore & Kyriazakis, 2006; Visser, 2014). The Large White is a large and late maturing pig (Visser, 2014). They have erect ears and fine white hair, with long bodies and good conformation for ham production (Whittemore & Kyriazakis, 2006). They are recognised as a universal dam breed, in that they are chosen for their sow's productivity, producing large litters with high survivability (Rothschild & Ruvinsky, 2011). Their offspring are good growers with good feed efficiency. Boars, when crossed with almost any purebred, will produce good bacon-type offspring. It is common to cross a female Large White with a Landrace, as the resulting female progeny has good reproductive capability (Visser, 2014). Table 2.1 reports the registered breed numbers in South Africa.

Figure 2.2 Large White pig (PBSSA, 2018a)

Development of the Landrace (Figure 2.3) began in 1895, as a descendent of Danish pigs. It is recognised as a high-quality pork and bacon producer, with efficient weight gain and feed efficiency. The breed is also known for high fertility and large litters (Visser, 2014). The Landrace is typically white with drooping ears, with high percentage carcass weight in the hams and loin, and good milk production (Whittemore & Kyriazakis, 2006). It was first imported to South Africa in 1952, and four years later the official progeny testing scheme was implemented which led to genetic improvement, resulting in the South African Landrace. The Landrace is recognised as a universal foundation dam breed (Visser, 2014). The number of registered Landrace pigs in SA can be found in Table 2.1.

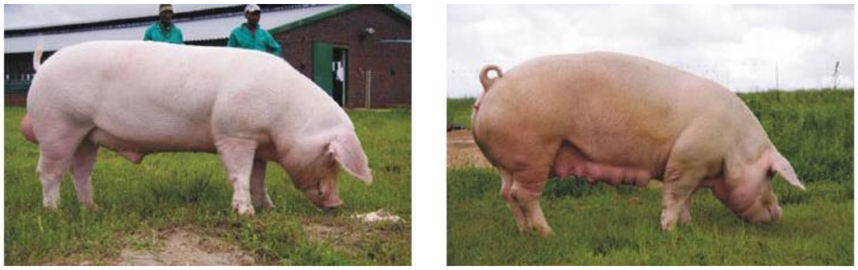

Figure 2.3 Landrace pig (PBSSA, 2018a)

The Duroc (Figure 2.4) originates from the North-Eastern United States of America, and has a distinct rusty, red colour and drooping ears (Whittemore & Kyriazakis, 2006; Visser, 2014). The first record of these red hogs is in 1872, and the first importations to South Africa were in 1980 (Visser, 2014). It is an important terminal sire breed, and pork quality is a main attribute, as well as efficiency in the finishing phase, and carcass quality (Whittemore & Kyriazakis, 2006; Rothschild & Ruvinsky, 2011). When crossed with the traditional white breeds, it produces litters with good growth rates and feed efficiency, remaining lean until higher slaughter weights. When crossbred, good quality carcasses, free from the problematic red hair follicles, are produced (Visser, 2014).

Figure 2.4 Duroc pig (PBSSA, 2018a)

The Duroc shows good muscling and marbling, good testicular development and libido, acceptable back fat levels and strong bone development, and stress susceptibility is negligible in this breed (Visser, 2014) as the RYR gene is not present (Alonso *et al*., 2015), making it a choice terminal sire. Durocs are not considered good mothers (PBSSA, 2018b). Sires are recommended to be used on first lines of Large White or Landrace crossbred sows, and all progeny marketed to maintain the 50% Duroc genetics required to result in meat quality improvement (Visser, 2014), eating quality improvement being due mainly to higher intramuscular fat (Whittemore & Kyriazakis, 2006; Alonso *et al*., 2015). Registered Duroc pig numbers can be found in Table 2.1.

Table 2.1 Number of registered pigs per breed on record in SA according to Pig Breeders Society of South Africa (2018a)

Breed	Males	Females
Duroc	63	295
Landrace	95	595
Large White	69	546

Table 2.1 is not a true reflection of the number of animals per breed in SA. The low number of registered animals for all three pure breeds in South Africa can be partly attributed to the costs and effort required for animal recording (2018, PBSSA, Pers.Comm., liezel@studbook.co.za). The number of pig stud breeders has shown a steady decline over the past two decades, due to the establishment of international companies providing genetic material to the industry. Stud breeders also tend to keep purebred records with their respective international databases (2018, Dr D. Visser, Pers. Comm., Juventis GeneTrade, danie@juventis.co.za).

2.3. Traits of economic importance

Profitable pig production depends upon reproductive and production efficiency, as well as consumer satisfaction (Visser, 2014). Merks *et al*. (2012) proposed that a novel phenotype is required to attain improved breeding goals, which would keep up with both efficiency and consumer demand. This novel phenotype has four main pillars: uniformity, vitality (reduction in losses without human interference), robustness (adapt to stressors without an effect on performance), and societal trends (while keeping up production efficiency). Thus, the traits of importance that will be discussed in this section will briefly refer to growth, and will focus on reproductive traits relating to sow fertility and mothering ability. Previously published heritability values (per trait) is summarised in Table 2.3.1 at the end of this section, as well as Table 2.3.2 illustrating correlations between selected litter traits.

2.3.1. Fertility traits

Fertility traits include those encompassing conception or farrowing rate, litter size, and piglet survival rate (Whittemore & Kyriazakis, 2006), and as such, may be loosely defined as a sow’s reproductive capability. Reproductive efficiency is usually defined as number of piglets produced per sow per year, in which multiple factors are involved (Whittemore & Kyriazakis, 2006; Vallet *et al*., 2016). According to Abell *et al*. (2012), a 0.1 improvement in litters per sow per year could lead to 11 less non-productive days per sow, and up to one more pig produced per sow per year. This trait is lowly heritable, but is possible to select for due to sufficient variation. However, reproductive failure, in that a sow is not producing adequate numbers of piglets, is still very common despite years of management improvement and gilt selection, and represents 33% of sow culls within herds (Rempel *et al*., 2015). Some reproductive traits of major importance in the dam line involve fertility and mothering ability, such as preweaning growth, body reserve loss in lactation, weaning to conception interval, temperament, number of piglets born alive, litter size at weaning, 21 day litter weight, ovulation rate, early sexual maturity, lactation efficiency, and teat number (Rothschild, 1996; Akanno *et al*., 2013; Yuan *et al*., 2015; Koketsu & Iida, 2017). A more recent, and very important, addition to this list is litter size at day 5 (LS5) (Nielsen *et al*., 2013; Yuan *et al*., 2015), and birth weight uniformity (Yuan *et al*., 2015; Tian *et al*., 2016).

Puberty (sexual maturity) in gilts is defined as the first oestrus seen due to boar stimulation, and as gilts make up a large number of any pig herd, earlier puberty will result in increased productivity, as well as stayability (Nonneman *et al*., 2016). Age at puberty and standing reflex are favourably correlated with age at first farrow, therefore selection on these traits should improve detection of oestrus and sow reproductive lifetime. However, the unfavourable correlation found by Knauer *et al*. (2011) between gilt growth rate and age at first farrow suggest that selection for growth may in turn lead to poor gilt performance, as shown by poor reproductive efficiency. Gilt performance can also be influenced by litter-of-origin effects, namely litter size. Gilts that were raised in smaller litters were shown to reach puberty earlier, and showed increased breeding herd retention (Vallet *et al*., 2016).

Teat number is directly related to mothering ability, which is important for piglet performance, and largely influences the number of piglets weaned (Verardo *et al*., 2015). While the selection for a higher number of teats leads to a higher number of functional teats (Chalkias *et al*., 2013), variation of teat number should also increase with a higher mean teat number. In contrast, there is no evidence to suggest a correlation between teat number and litter size, which would have been beneficial (Felleki & Lundeheim, 2013; Lundeheim *et al*., 2016). The event of more piglets than functional teats is highly probable, due to the higher variability of litter size in comparison to the variability of teat number (Felleki & Lundeheim, 2013).

Litter size is a function of ovulation rate, conception rate, and embryonic/foetal survival (Rutherford *et al*., 2013). In order to improve litter size, fertility, ovulation rate, uterine capacity, and embryo survival must be simultaneously improved (Whittemore & Kyriazakis, 2006). Uterine capacity in particular, if increased, can improve prenatal survival (Freking *et al*., 2016). Since it is difficult to select for directly, LS5 has become a useful indicator to improve survival (Nielsen *et al*., 2013; Yuan *et al*., 2015; Freking *et al*., 2016). Selection for increased uterine capacity has shown a slight decrease in ovulation rate, but an increase in foetus survival without altering foetal weight (Freking *et al*., 2016). Marantidis *et al*. (2013) stated that litter size has a direct effect on a sow's productivity and so a direct effect on the profit of the farmer, and that reproductive improvement seems to be far more influential than environmental improvement. Larger litters are important for sow productivity, but the rapid increase in ovulation rates in the pig industry has led to below optimal survival rate of piglets, prenatal and postnatal (Marantidis *et al*., 2013). There is also an important dynamic between litter size and the ability of a sow to use body reserves for milk production. As litters increase in number and size due to selection, a higher quantity and quality of milk is required for optimal health and growth of the litter. In order to produce this, sows must make use of their body reserves. However, as pigs have been selected for leanness, feed intake and body reserves have also decreased. The poor body condition of sows at weaning leads to poor reproductive performance in the following parity, and this is especially apparent at first parity weaning, as sows had to further subdivide their body reserves for their own continued growth (Lundgren *et al*., 2014). The increase in selection for prolificacy has also led to an increase in within-litter piglet birth weight variation (Yuan *et al*., 2015; Magnabosco *et al*., 2016; Pietruszka *et al*., 2017).

Birth weight variation affects pig herd productivity, due to its effect on post-weaning performance and piglet survival (Zindove *et al*., 2013; Marandu *et al*., 2015). Litter uniformity is generally determined by measuring within-litter weight coefficient of variation at birth (CVB) or standard deviation analysis, and has a heritability of 0.06-0.11 (Sell-Kubiak *et al*., 2015a; Tian *et al*., 2016). There is limited information on birth weight variation within litters and its effects on weight gain and weaning weights, as well as piglet survival, although it appears that there is a negative relationship between survival rate and variation (Muns *et al*., 2014; Marandu *et al*., 2015). It is hypothesised that the increase in mortality is due to the increase in lower birth weights that comes with variability, rather than variability itself. Additionally, mortality of the lower weight piglets is understood to increase when placed with larger piglets, suggesting that competition plays a role. The intrinsic variability in teat productivity can lead to variation in relatively uniform litters (Muns *et al*.,2014), and presumably has an influence on the apparent increase in variation as varied littermates develop (Vaclavkova *et al*., 2012; Magnabosco *et al*., 2015). Day 30 has been shown to be an important point in gestation, as within-litter variability in weights at birth mirrors that of the foetal weight at this point (Whittemore & Kyriazakis, 2006). Embryos being carried by an individual female can vary considerably in their stage of development, with this within-litter variability affecting embryo survival itself. Some more developed blastocysts have a better chance of survival due to changes in the uterus and effects of competition (Whittemore & Kyriazakis, 2006). A certain amount of variation can also be attributed to sex, as at various stages of gestation, female piglets are lighter than male piglets, with less muscle mass, presumably due to the effects of testosterone (Palencia *et al*., 2017).

2.3.2. Pre-weaning growth traits

It is important to note that growth and mortality of piglets are dependent on both direct additive and maternal additive genetic components (Högberg & Rydhmer, 2010). Preweaning growth is particularly influenced by maternal effects, both environmentally and genetically (Tomiyama *et al*., 2010). Certain weights are important markers in the development of a piglet. Zindove *et al*. (2013) highlighted that 21 day weight measurement is important, as important biological and immunological changes take place at this stage that impact future performance such as growth and vitality. The coefficient of weight variation at 3 weeks is similar to that at birth, and mean weight at birth is correlated with mean weight at 3 weeks (Zindove *et al*., 2013). The weight of her piglets at 3 weeks is a good indicator of a sow's mothering ability, as they are almost fully dependent upon her milk supply until this point (Högberg & Rydhmer, 2010). The weight at weaning is important as the trauma experienced by the piglet in this process leads to reduced feed intake and often health issues and a larger fat storage, which means a loss of productivity (Whittemore & Kyriazakis, 2006). Weaning weight has not been linked to litter size (Beaulieu *et al*., 2014; Vermeulen *et al*., 2016). It has, however, been found that a greater birth weight leads to a greater weaning weight, due partly to a greater daily gain from birth to weaning (Beaulieu *et al*., 2014; Vermeulen *et al*., 2016). This may also be due to lower birth weight piglets having fewer muscle fibres and less developed intestines and livers, leading to lower growth rates pre-wean and post-wean (Pietruszka *et al*., 2017).

Table 2.2 A summary of heritability estimates for sow reproductive traits and pre-weaning piglet performance

Trait	h^2 range	Breeds used	References
Number born alive	0.06-0.19	Duroc, Hampshire, Landrace, Large White, Tai Zumu, Yorkshire, others unknown	Rothschild, 1996; Hermesch & Luxford, 2000; Chen *et al*., 2003; Visser, 2004; Arango *et al*., 2005; Högberg & Rydhmer, 2010; Lundgren, 2011; Rothschild & Ruvisnky, 2011; Dube *et al*., 2012; Akanno *et al*., 2013; Visser, 2014; Banville *et al*., 2015
Litter birth weight	0.10-0.29	Landrace, Large White, others unknown	Rothschild, 1996; Hermesch & Luxford, 2000; Rothschild & Ruvisnky, 2011; Dube *et al*., 2012; Akanno *et al*., 2013; Noppibool & Elzo, 2016
Individual birth weight	0.02-0.27	Berkshire, Duroc/Landrace/Large White cross, Landrace, Large White, Yorkshire	Kauffman *et al*., 2000; Tomiyama *et al*., 2010; Dufrasne *et al*., 2013, Alves *et al*., 2018
Mean birth weight	0.43-0.51	Landrace, Yorkshire	Högberg & Rydhmer, 2010
Litter uniformity (birth weight)	0.06-0.33	Landrace, Large White, others unknown	Lundgren, 2011; Sell-Kubiak *et al*., 2015b; Tian *et al*., 2016
Litter size at 21 days	0.10-0.16	Landrace, Yorkshire	Högberg & Rydhmer, 2010
Mean 21 day weight	0.26-0.34	Landrace, Yorkshire	Högberg & Rydhmer, 2010
Litter size at weaning	0.02-0.24	Czech Landrace, Czech Large White, Duroc, Hampshire, Landrace, Tai Zumu, Yorkshire, others unknown	Rothschild, 1996; Chen *et al*., 2003; Visser, 2004; Rothschild & Ruvisnky, 2011;; Akanno *et al*., 2013; Banville *et al*., 2015; Krupa *et al*., 2016; Noppibool & Elzo, 2016
Preweaning mortality	0.07-0.33	Duroc, Landrace, Large White	Dufrasne *et al*., 2013
Litter weaning weight	0.15-0.23	Landrace, Yorskhire	Noppibool & Elzo, 2016
Individual weaning weight	0.01-0.16	Large White, Landrace, Yorkshire	Kauffman *et al*., 2000; Tomiyama *et al*., 2010; Alves *et al*., 2018
Weaning to conception interval	0.08-0.30	Unknown	Rothschild, 1996; Visser, 2004; Akanno *et al*., 2013
Ovulation rate	0.30-0.39	Unknown	Rothschild, 1996; Visser, 2004; Bidanel, 2011

Table 2.2 Continued

Trait	**H^2**	**Breeds used**	**References**
Oestrus length (days)	0.22	Landrace, Large White	Knauer *et al*., 2011
Teat number	0.01-0.52	Czech Landrace, Czech Large White, Tai Zumu, others unknown	Visser, 2004; Tomiyama *et al*., 2010; Visser, 2014; Banville *et al*., 2015; Krupa *et al*., 2016
Age at puberty (days)	0.29	Landrace, Large White	Knauer *et al*., 2011
Age at first farrow (days)	0.22-0.23	Landrace, Large White, others unknown	Knauer *et al*., 2011; Akanno *et al*., 2013
Average daily gain	0.19-0.5	Duroc, Czech Landrace, French Landrace, French Large White, Czech Large White, Landrace, Polish Large White, others unknown	Kaplon *et al*., 1990; Lo *et al*., 1992; Ducos *et al*., 1993; Suzuki *et al*., 2005; Rothschild & Ruvisnky, 2011; Akanno *et al*., 2013; Krupa *et al*., 2016
Milk yield	0.15-0.25	Unknown	Visser, 2014
Milk quality	0.30-0.5	Unknown	Visser, 2014

h^2 = heritability

Correlations must be considered alongside heritability, as traits may be unfavourably correlated. From Table 2.2 it can be seen, for example, that mean birth weight and within-litter birth weight variation are negatively genetically correlated (-0.49) (Milligan *et al*., 2002), indicating that as variation increases, birth weight will decrease. This can be seen as favourable, as it would benefit the farmer to decrease variation, and increase birth weight. An unfavourable genetic correlation can be found between within-litter birth weight variation and number born alive (-0.24-(-0.39)) (Zindove *et al*., 2013; Tian *et al*., 2016; Kennedy, 2017), however, indicating that as litter size increases, uniformity will inevitably, and unfavourably, decreases.

Table 2.3 A summary of genetic correlations between selected litter traits from literature (Milligan *et al*., 2002; Dufrasne *et al*., 2013; Zindove *et al*., 2013; Beaulieu *et al*., 2014; Krüger, 2015; Tian *et al*., 2016; Kennedy, 2017; Alves *et al*., 2018)

	LSF	**NBA**	**BiW**	**MBiW**	**LBiW**	**CVB**	**21W**	**M21W**	**L21W**	**28W**	**M28W**	**L28W**	**SURVW**	**MORT**
LSF	-	-	-0.66	-	-	-	-0.70	-	-	-0.53	-	-	-	-
NBA		-	-0.29	-0.46	0.43-0.79	0.24-0.39	-	-0.15	-	-0.10	-0.35-(-0.13)	0.33-0.55	-0.27-(-0.18)	-
BiW			-	-	-	-	-	-	-	0.55	-	-	-	-0.21-(-0.52)
MBiW				-	-	-0.49	-	0.47	-	-	0.17-0.78	-	0.14-0.43	-
LBiW					-	-0.12-(-0.13)	-	-	-	-	-	0.57-0.63	-	-
CVB						-	-	-0.13	-	-	-0.18-(-0.09)	-0.03-0.29	-0.34-(-0.23)	-
21W							-	-	-	-	-	-	-	-
M21W								-	-	-	-	-	-	-
L21W									-	-	-	-	-	-
28W										-	-	-	-	-0.30
M28W											-	-	-0.02	-
L28W												-	-	-
SURVW													-	-
MORT														-

LSF = litter size at farrowing; MORT = pre-weaning mortality; BiW = individual birth weight; 21W = individual 21 day weight; 28W = individual weaning weight; NBA = number born alive; MBiW = mean birth weight; CVB = within-litter coefficient of variation at birth, M21W = mean weight at 3 weeks; M28W = mean weight at weaning; SURVW = survival to weaning; LBiW = litter weight at birth; L21W = litter weight at 3 weeks; L28W = litter weight at weaning

2.4. Piglet birth weight uniformity

Prolificacy is a trait of great interest in the pig industry. There has been an international increase in litter size from 10.2 in 1999, to 11 in 2009 (Zindove *et al*., 2013; Magnabosco *et al*., 2015). The 2017 average for SA was 13.5 piglets per litter (2018, SAPPO, Pers. Comm., info@sapork.com). Topigs' sows have production targets which include >14 piglets born alive and >12 weaned per litter (Topigs, 2018b), and PIC (2018b) includes vigorous and uniform piglets in their sow line description. Number born alive has been a main focus of the industry in order to maximise sow productivity. However, it has been shown that larger litter sizes are negatively correlated to survival rates, weight gains, and weaning weight (Václavková *et al*., 2012; Zindove *et al*., 2013; Magnabosco *et al*., 2016). Pre-weaning mortality has been reported to be as high as 20-25% (Nielsen *et al*., 2016). The increase in litter size has also been shown to correlate with a decrease in mean piglet birth weight, and an increase in within-litter birth weight variation, as well as an increase in lighter piglets (below 1kg), which is particularly prevalent within less uniform litters (Václavková *et al*., 2012; Alvarenga *et al*., 2013; Magnabosco *et al*., 2015, 2016; Yuan *et al*., 2015). A critical birth weight of 0.95-1.1kg is recommended to reduce mortality and increase vitality, as below this threshold, myofibre and lipid development is negatively affected, and postnatal compensation is rare (Václavková *et al*., 2012; Magnabosco *et al*., 2015).

An average piglet birth weight is around 1.2-1.5kg, as found in purebred Norsvin Landrace and Canadian synthetic line pigs (Lundgren, 2011; Beaulieu *et al*., 2014). A normally distributed (Gaussian) pig population is expected to deviate from the mean weight relatively predictably, with 68.3% within 1 standard deviation (SD) point, 95.5% within 2 SD, and 99.7% within 3 SD (ThePigSite, 2017). Another means to identify variation is explained by Rutherford *et al*. (2013), where piglets weighing below the tenth percentile (in terms of litter average) at birth, while displaying normal allometry, are considered small for gestational age (SGA), of which there would be more in the case of within-litter variation. In highly variable litters, distribution may be so negatively skewed that the majority of birth weights lie well below the mean birth weight of the litter (Yuan *et al*., 2015).

2.4.1. Effect of birth weight variation

2.4.1.1 Performance

In the case of larger litter size, which leads to higher birth weight variation (Yuan *et al*., 2015; Magnabosco *et al*., 2016; Pietruszka *et al*., 2017), the uterine blood flow is insufficient for the number of foetuses, leading to decreased nutrient supply to the foetuses (Václavková *et al*., 2012). This negatively affects the number of muscle fibres, which restricts postnatal growth causing fat deposits, and so, decreased quality pork (Alvarenga *et al*., 2013; Dhakal *et al*., 2013; Pardo *et al*., 2013a; Beaulieu *et al*., 2014; Yuan *et al*., 2015). The formation of secondary muscle fibres is most susceptible to intrauterine environmental stressors between 55 and 95 days into gestation, which decreases muscle mass and post-natal performance, including adverse influences on meat quality due possibly to fewer total and primary muscles (Pardo *et al*., 2013a; Beaulieu *et* *al*., 2014; Yuan *et al*., 2015; Tian *et al*., 2016; Palencia *et al*., 2017). Beaulieu *et al*. (2014) reported that the best meat quality (based on pH and drip loss) was from middle birth weight piglets (1.23-1.53 kg) and the poorest from lighter birth weight (0.80-1.23 kg). It was suggested that this was due to excessive fiber hypertrophy and giant fibres. In contrast, Bérard *et al*., (2008) found that birth weight had minimal effects on meat quality, possibly because of low hypertrophy due to the lack of the porcine stress syndrome gene in the line being studied. It has also been found that low birth weight has a larger effect on the carcass composition of female pigs than male pigs (Alvarenga *et al*., 2013; Pardo *et al*., 2013a; b). Reproductively, light weight gilts have been shown to produce 4.5 less piglets over three parities than their heavier litter mates, and this is thought to be due to compromised postnatal follicular development of the runts, resulting in few primary follicles and no secondary follicles at birth. Higher insulin and insulin-like growth factor secretion in heavier gilts may also help in reducing follicular atresia, allowing larger litter sizes (Magnabosco *et al*., 2016). However, Vallet *et al*. (2016) found that larger piglets at birth were prone to later onset of puberty, which was exacerbated by slow preweaning growth.

Piglets with a lower birth weight, being more common in variable litters, have been found to attain lower growth rates (Alvarenga *et al*., 2013; Dhakal *et al*., 2013; Cutshaw *et al*., 2014a). It has been reported by Beaulieu *et al*. (2014) that low birth weight piglets resulted in almost 10 extra days to reach market weight compared to the heavier piglets in the litter. Yuan *et al*. (2015) confirmed this with similar results, indicating three additional weeks were required to reach 25kg for light vs heavier littermates. The cause for the poorer performance of lower birth weight piglets is thought to be mainly due to larger piglets excluding smaller piglets from the more productive teats (Pardo *et al*., 2013b; Yuan *et al*., 2015), and also suckling more effectively which directs more nutrients and hormones related to milk production to these teats (Zindove *et al*., 2013). The lower suckling rate of the lighter piglets caused by this competition leads to lower consumption of colostrum and milk, which leads to poor passive immunity and a generally low nutritional status, increasing mortality rate and decreasing growth rate (Campos *et al*., 2012; Yuan *et al*., 2015).

The “teat order” phenomenon is when piglets form a teat hierarchy according to vigour, and continually return to the same teat. This means that larger litter sizes force more piglets to consistently suckle under-productive teats, which are found at the posterior of the sow (Rutherford *et al*., 2013; Yuan *et al*., 2015). Smaller piglets also show inefficient utilisation of nutrients due to physiological immaturity at birth, such as maldeveloped organ systems (muscles, liver, intestines, kidneys, heart) (Pardo *et al*., 2013a; b; Rutherford *et al*., 2013; Yuan *et al*., 2015). The poor performance could permanently decrease postnatal growth (Yuan *et al*., 2015). Lighter piglets have lower thermoregulatory ability, as they have less insulation, and also have a higher body surface to weight ratio, making them more prone to hypothermia. They take longer to reach the udder and consequently take in less colostrum and milk. This has a direct effect on piglet survival and performance, through lack of passive immunity and undernourishment (Panzardi *et al*., 2013).

2.4.1.2 Welfare

Survival to weaning is a product of piglet welfare. From a genetic perspective, pre-weaning survival and within-litter birth weight uniformity is favourably correlated. The relationship between the coefficient of variation for within-litter birth weight and piglet survival is linear, and the relationship between average birth weight and mortality is curvilinear (Alvarenga *et al*., 2013; Pardo *et al*., 2013b; Yuan *et al*., 2015; Tian *et al*., 2016). Birth weight variation is also lowly correlated to survival to weaning, indicating that more uniform litters have higher survival rates (Lundgren, 2011; Zindove *et al*., 2013), and thus better welfare. Marandu *et al*. (2015) reported that individual birth weight had a larger influence on piglet survival than did relative birth weight, as well as males having a higher mortality rate due to higher basal cortisol levels and therefore higher stress susceptibility. Higher within-litter variability leads to higher risk of mortality before weaning as there is a higher proportion of lighter piglets that must compete with heavier piglets. This competition also leads to smaller piglets remaining near the sow for longer, leading to a higher chance of being crushed (Yuan *et al*., 2015). It was concluded that moderately sized litters (10-14) have the highest survival rates (Marandu *et al*., 2015).

Poor development, milk intake, and nutrient utilisation leads to piglets whose wellbeing is compromised in comparison to their heavier counterparts. Piglets suffering from intra-uterine growth restriction (IUGR), a common cause of within-litter variation to be explained in detail further on, are also generally more susceptible to morbidity/mortality due to maldevelopment of several organ systems (Rutherford *et al*., 2013; Magnabosco *et al*., 2015; Yuan *et al*., 2015). Piglets that are exposed to intrauterine restriction have lower colostrum intake and hepatic glycogen which increases morbidity and mortality, and these smaller piglets are also more likely to suffer hypothermia (Campos *et al*., 2012; Magnabosco *et al*., 2015). Spontaneous IUGR has been found to interact with developmental patterns of genes in subcutaneous adipose tissue during gestation, particularly Insulin-like Growth Factor (IGF), leading to lower adipose tissue in low birth weight piglets (Gondret *et al*., 2013). Adipose (white) tissue development before birth is important for insulation, as an energy reserve and may have a role in overall maturity of piglets. The effects are, however, temporary, and the smaller piglets show an accelerated fat accretion during suckling (Gondret *et al*., 2013). The liver, having a major role in nutrient utilisation, as well as other important organ systems such the gastrointestinal tract and thymus, have been found to be particularly affected by IUGR, showing abnormalities in metabolism, development, and function (Liu *et al*., 2013; Rutherford *et al*., 2013).

2.4.1.3 Management

Piglets with low uniformity require more complicated management, such as small piglets requiring more days than larger littermates to reach market weight, thereby increasing costs such as feeding (Yuan *et al*., 2015; Tian *et al*., 2016). Cross fostering is a common practise in the pig industry to level out litter numbers, match litter size to teat number, and reduce the effects of birth weight variation (Heim *et al*., 2012), which requires extra labour and time. Variation is particularly problematic in the typical all-in all-out system, as pigs must often then be sorted according to weight instead of according to age. The all-in-all-out system also prevents disease transmission by breaking the chain of infection and preventing pathogen build-up, as the facility can be sanitized between groups. Additionally, the system improves feed efficiency and daily gain, leading to less days to marketing and lower feed costs (ThePigSite, 2012). Higher uniformity allows easier management and lower mortality rates, and uniform size and weight of product as well as quality (colour, marbling, drip loss) is useful for retailers and consumers (Merks *et al*., 2012). Pig weight variation at marketing and processing, due to variation in size and shape, also leads to handling difficulties and product uniformity issues, which is undesirable (Zindove *et al*., 2013; Mulder *et al*., 2015). As slaughter and management issues affect profitability, it appears to be a better option to select for sows which produce more uniform litters (Zindove *et al*., 2013).

2.4.2. Non-genetic factors influencing uniformity

2.4.2.1 Effect of environment

Litter size is determined by the number of released and fertilised oocytes that develop into viable piglets. Quality of the oocyte may be an important determinant of embryo viability and survival, with quality being a product of the maternal environment including the nutrition, temperature, and age of the dam (Swinbourne *et al*., 2014). Pigs are prone to heat stress as they have low sweating capability and must rely mainly on evaporative cooling (Boddicker *et al*., 2014). This has been exacerbated by modern genetic selection, as pigs are selected for higher lean tissue accretion, thereby increasing basal heat production (Johnson *et al*., 2015). Heat stress experienced in gestation has been shown to alter growth, body composition, and metabolic function in piglets, with severity particularly depending on the time and duration of the stress (Boddicker *et al*., 2014; Johnson *et al*., 2015). Alterations are due to the changes in metabolism and uterine blood flow, causing altered skeletal development, impaired intestinal development, and reduced growth performance, as well as altering hormonal and metabolic profiles, affecting piglet development and performance (Dhakal *et al*., 2013; Boddicker *et al*., 2014). Some piglets may be more affected than others, due to placental vascularity differences *in utero* (Rutherford *et al*., 2013), thereby affecting development and causing weight variation.

Swinbourne *et al*. (2014) found that reduction in size of oocytes during warmer seasons, and not meiotic competence, produces smaller litters. This appears to be primarily due to the effect of heat on hormone production, affecting developmental competence of the oocytes. When gestating sows are exposed to heat stress conditions at different periods, the first half of gestation seems to be more detrimental (Boddicker *et al*., 2014). Primary and secondary muscle fibre hyperplasia ceases at day 35 and 90 of gestation in pigs, and fibre number limits muscle mass capacity in postnatal life, hence heat stress in the first half of gestation impairs primary fibre development causing permanent negative effects on performance (Boddicker *et al*., 2014). Reduced organ size was also found in heat stress piglets, especially the liver, which is linked with a lower fasting heat production (Johnson *et al*., 2015). The liver is an important source of energy for locomotion and thermoregulation for the first 2 days of life, as it has the highest concentration of glycogen in the body (Theil *et al*., 2014). As these issues affect individual piglets differently *in utero*, it may have an effect on within-litter birth weight variation.

Campos *et al*. (2012) suggested that sow feed intake during gestation is a factor in piglet birth weight uniformity. Feeding of cycling gilts at maintenance level or below, compared to *ad libitum*, led to a reduction in the maturation of oocytes (Swinbourne *et al*., 2014). Oocyte maturation at different rates within the uterus, due to possibly differing nutrient availability to foetuses, may lead to foetus weight variation. The litter-of-origin effect may also influence gilts' future reproductive efficiency, as competition decreases colostrum availability in larger litters, resulting in decreased neonatal uterine gland development (Vallet *et al*., 2016).

2.4.2.2 Effect of dam

The birth weight of the dam has a negligible effect upon her reproductive performance (Almeida *et al*., 2015). Ovarian development at both 80 days and post-puberty were unaffected by it, so ovulation rate was not associated with birth weight. Small litters in these low birth weight gilts, especially in the first and second parity, was reported to be due rather to lower mating weight or growth rate at mating (Filha *et al*., 2010; Roongsitthichai *et al*., 2014). High body condition loss during lactation by the dam, however, is implicated in increasing birth weight variation. Gonadotropin Releasing Hormone (GnRH) secretion can be decreased or inhibited due to the condition loss, causing insufficient restoration of follicle development, which affects ovulation rate and embryo quality (Wientjes *et al*., 2013b). This insufficient development may cause increased developmental variation within the preovulatory follicles, affecting embryo survival and development, and luteal development, thereby affecting piglet birth weight and litter uniformity (Rutherford *et al*., 2013; Wientjes *et al*., 2013b). In particular, protein mobilisation of 9-12% of the parturition protein mass can compromise follicular development (Bierhals *et al*., 2012), which in turn will lead to compromised foetal development. Additionally, the duration of ovulation may have an effect on within-litter variation, as follicular diversity is associated with embryonic diversity (Lundgren, 2011; Yuan *et al*., 2015). The more developed blastocysts begin to synthesise oestradiol sooner, which may affect elongation and implantation (Rutherford *et al*., 2013; Yuan *et al*., 2015).

Placental insufficiency has been suggested as reason for birth weight and litter size differences between parities. It is proposed that gilts, especially those with inherently low placental efficiency (e.g. Western breeds) (Mesa *et al*., 2015), have limited uterine space for the growth of the placenta, thus affecting the birth weight and foetus survival (Père & Etienne, 2000). The longer uteri of older sows allow for better expression of placental growth potential. An alternative suggestion is that older sows have greater uterine blood flow, affecting the total mass of fetoplacental units that can be supported (Mesa *et al*., 2015).

Uterine capacity and post-natal mothering ability differs between breeds (Campos *et al*., 2012). The uterine capacity of the highly prolific Meishan breed is higher than the Western breeds, due to the placental vascularity increasing rather than placental size. This diminishes competition between conceptuses for nutrients, producing similar sized piglets to Western breeds despite smaller placentas (Mesa *et al*., 2015). Meishan sows are also known for a higher ovulation rate, due to higher recruitment and lower atresia, as well as a better follicular environment for oocyte maturation (Silva *et al*., 2014). According to Gondret *et al*. (2013), maternal characteristics contribute very little to the heterogeneity of litters, but placental insufficiency leading to foetal undernutrition, with reduced foetal size being seen as an adaption mechanism, has been recognised as a main factor in selective intra-uterine growth retardation (IUGR). IUGR is defined as insufficient growth and development of the embryo/foetus during pregnancy, with selective IUGR leading to variation within the litter, usually seen as a weight less than 2 standard deviations of the mean body weight for the given gestational age (Liu *et al*., 2013). This is quite prominent and serious in multi-foetal animals such as the pig (Rutherford *et al*., 2013; Dong *et al*., 2016). IUGR has a significant effect on neonatal survival as well as postnatal growth and immunity, and has an important effect on development and barrier functions of the intestine, causing long-term growth impairment (Yuan *et al*., 2015; Dong *et al*., 2016). These factors will exacerbate within-litter heterogeneity. One of the primary causes of IUGR is placental inefficiency, which is the inability of the placenta to supply nutrients to foetuses. Placental capability is dependent on blood flow and area of placental exchange, making endometrial surface area, or uterine capacity, critical (Mesa *et al*., 2015; Yuan *et al*., 2015).

Intrauterine crowding has been associated with the decreasing weight/increasing litter size phenomenon (Alvarenga *et al*., 2013; Wang *et al*., 2017). With genetic and epigenetic factors, this can lead to changes in angiogenesis, growth, and vascularisation of the placenta, so that nutrient and oxygen supply to the foetuses is negatively affected (Václavková *et al*., 2012). It is also reported that as the litter size increases, so does uterine blood flow, but still to a lesser extent than is required for the number of foetuses, which means less uterine blood flow per foetus, resulting in lower nutrient supply (Vaclavkova *et al*., 2012). Some foetuses may receive more blood flow than others, leading to variation. At the ovarian end of the horn, foetuses were found to be 10% heavier than those found in the middle or near the cervix. This is more notable in the last third of gestation, when maternal transfer of nutrients to foetuses is greatest, leading to the hypothesis that vascular density varies along the uterine wall, affecting foetal growth in certain positions (Yuan *et al*., 2015). The position *in utero* was not found to affect primary muscle fibre characteristics, however. The effects seen on growth due to position may also be attributed to lesser foetuses in these areas of the uterus and thus less competition for space and nutrients (Palencia *et al*., 2017). The effect of position *in utero* is, as yet, unclear.

Zindove *et al*. (2013) stated that there was a linear relationship between birth weight variation and survival to 3 weeks, but that it was different across parities. It was suggested that this may be due to the changes in milk production with age, as primiparous sows experience higher postpartum stress due to the need for new adaptions to farrowing and lactation. It is further suggested that the variation may be increased up to 3 weeks due to higher competition for limited milk supply (Zindove *et al*., 2013). The physiological immaturity of a primiparous sow and the usually overweight condition or reduced uterine efficiency of older sows, and therefore parity itself, is considered a factor in development and performance of piglets (Zindove *et al*., 2013). Older sows are more prone to producing less uniform litters, as well as a higher proportion of lower birth weight piglets. It is postulated that this may be due to deterioration of oocyte quality with age (Yuan *et al*., 2015).

2.4.3. Uniformity improvement strategies

2.4.3.1 Litter size

Zindove *et al*. (2013) and Marandu *et al*. (2015) advocate that it is not in the best interest of the industry to decrease litter size due to its impact on profit. As increased litter size will always be important in the pig industry, a new trait of interest has become litter size at day 5. This takes into account peri-natal mortality, allowing the selection of stronger litters (Rutherford *et al*., 2013). Survival to day 6 has increased by 6%, decreasing overall mortality by 20% in Danish herds (Nielsen *et al*., 2013). Selecting based on LS5 also increased total number born by 1.9 and 1.3 per litter in Danish Large White and Landrace litters (Putz *et al*., 2015).

Larger litters require more nutrients, both before and after farrow. Increased litter size particularly elicits a higher milk production, which leads to increased body reserve mobilisation in order to maintain production, due, in part, to suckling intensity (Lundgren, 2011). Sow body condition loss affects follicular development and thereby compromises foetal development, affecting litter uniformity (Rutherford *et al*., 2013; Wientjes *et al*., 2013b). The sow has limited capability to compensate with increased feed intake, and low intake affects reproductive hormone levels, particularly those that affect follicle development. This can negatively affect post-lactational performance by delaying return to follicular development and oestrus (Lundgren, 2011; Bierhals *et al*., 2012), so fostering out is practised to relieve the strain of larger litters rather than selecting against it.

2.4.3.2 Management

Cross fostering is a common practise in the pig industry to level out litter numbers, match litter size to teat number, and reduce the effects of birth weight variation, such as preweaning mortality, although the effects have not been properly quantified (Heim *et al*., 2012; Muns *et al*., 2014). Fostering should take place between 12 hours and 24 hours postpartum, as before this it is important for piglets to consume their genetic dam's colostrum during the prime immunoglobulin absorption period (Heim *et al*., 2012). This is especially important as piglets are unable to absorb colostrum immunoglobulins other than those of their mother, and thus other colostrum cannot confer passive immunity (Heim *et al*., 2012; Quesnel *et al*., 2012). After 24 hours, gut permeability begins to drop and teat order has begun to be established, and the sow will also be less inclined to accept outside piglets as she has begun to recognise her own by olfactory cues. Piglets are, likewise, able to recognise their dam as early as 12 hours old, and fewer nursing episodes are missed due to stressed behaviour when fostering occurs within a day (Heim *et al*., 2012).

Lactation is an important period for low birth weight piglets to exhibit compensatory growth, as the average daily gain (ADG) during this period is positively associated with lifetime ADG (Dhakal *et al*., 2013). In the study of Heim *et al*. (2012), low birth weight piglets missed more nursing episodes when raised in large litters mixed with medium and large piglets, than when raised in small litters. Cross-fostering is practised in order to obtain more homogenous weights within suckling litters to increase survival and pre-wean growth, where smaller piglets from primiparous sows are often moved to multiparous sows due to their higher lactation potential, as they have larger mammary glands (Bierhals *et al*., 2012). Fostering on is practised with litters smaller than the number of functional teats, as it leads to greater stimulation of the mammary complex and higher milk production (Bierhals *et al*., 2012). Continuous cross-fostering (throughout suckling) to maintain weight homogeneity is not recommended as it can be very stressful for both piglet and sow, and can have effects on behaviour which affect pre-wean growth. It also increases the chance of infection as piglets are constantly being exposed to new environments with pathogenic agents which they do not have adequate protection against (Heim *et al*., 2012). Marandu *et al*. (2015) reported a higher risk of mortality, lower growth rate, and lower weaning weight when cross fostering. This may be due to littermates not properly adjusting to each other, or due to piglets being transferred from a poor sow which had a permanent effect on their vitality. Heim *et al*. (2012) also shows poorer growth in piglets nursed by foster dams than piglets nursed by their biological dam. The weaning weight has been shown to improve in lower birth weight piglets when moved to more uniform litters, but the effects did not persist to slaughter (Douglas *et al*., 2013). Giving supplementary milk to smaller piglets, however, does seem to decrease coefficient of variation (CV) within the litter to slaughter (Douglas *et al*., 2013)

Post-farrow intake is generally low, and increases through lactation with a peak around 7-19 days post-farrow, while peak lactation occurs at 21 days post-farrow. However, body reserves are still often mobilised due to the lag, particularly in primiparous sows, who often cannot meet both maintenance and lactational nutrient requirements (Bierhals *et al*., 2012). Therefore, nutritional assistance should be particularly directed at primiparous sows, to prevent ovulation issues in the following oestrus. Focus has been placed upon pre-ovulation, peri-implantation, and late gestation diets to increase homogeneity of oocytes and conceptuses. It has been found that feeding insulin-stimulating diets to sows before mating improved litter uniformity (Wientjes *et al*., 2013a), as does improvement of lactation nutrition (Van Barneveld & Hewitt, 2016). There was a positive relationship seen between pre-mating insulin levels in the blood and lutenizing hormone, follicle development (Yuan *et al*., 2015), the ensuing progesterone levels (affecting luteal development), and embryo size at day 10 during pregnancy (Wientjes *et al*., 2013a). However, conflicting results have been found (Wientjes *et al*., 2012), showing that follicle development, as well as luteal, foetal and placental development, were not affected by the insulin-stimulating diets before mating. The inconsistency of results is suggested to be due to differences in sow parity and body condition losses in lactation or the differences in insulin feeding periods between the studies (Wientjies *et al*., 2013a). Arginine and glutamine have also been found to be important in gestating sow diets, to reduce litter birth weight variation (Van Barneveld & Hewitt, 2016). The source of energy for the gestating sow has been shown to have an effect on glycogen stores in the piglets, having a large effect on survival rate (Theil *et al*., 2014). Dietary fat and fibre in the diet of the sow appears to alter the production of colostrum, the fat content of colostrum, and the immunoglobulin content of the colostrum, all important for the well-being of the piglet, which could decrease morbidity in the smaller piglets (Theil *et al*., 2014).

Piglets that undergo IUGR experience a foetal adaptive reaction to deal with placental insufficiency, known as the “brain sparing effect,” which is the prioritizing of brain development. Normal piglets will have flat heads, whereas IUGR piglets will be small with “dolphin-like” heads (Douglas *et al*., 2016). Therefore, head shape and size offer farmers a way of identifying underweight piglets in a varied litter, who may need intervention to ensure survival and normal post-natal development. Alternatively, at-risk piglets can be identified via body mass index (birth weight divided by crown-rump length squared), which has been evidenced to be more accurate than birth weight (Dong *et al*., 2016; Douglas *et al*., 2016). Butyrate is a carboxylic acid that can be given to piglets to protect the intestine by inhibiting the growth of bacteria, increasing mucosal cell proliferation, and improving intestinal cell development, as well as improving immunity and stimulating feed intake and body growth when supplemented pre-weaning (Dong *et al*., 2016). This is particularly important in IUGR piglets, who have suffered mal-development of the intestine. Muns *et al*. (2014) found that oral supplementation of colostrum had no effect on litter mortality, but admitted that it could have been due to insufficient volumes administered. Ferrari *et al*. (2014) suggested that a minimum of 200 g of colostrum will provide passive immunity, reducing pre-wean mortality and offering slight weight gain, but it also largely depended on the weight of the individual piglet.

2.4.3.3 Genetic selection

The improvement in genetics seen in the past can be ascribed to statistical method developments which removed and overcame many non-genetic sources of variation found in field data (Cutshaw *et al*., 2014b). The introduction of best linear unbiased prediction (BLUP) has allowed for improved genetic selection (Rutherford *et al*., 2013). Since the heritability of birth weight uniformity is 0.06-0.33 (Table 2.1), it suggests that progress would be slow but possible due to low to moderate heritability, along with a relatively short generation interval facilitated by frequent replacement of nucleus animals, and assuming sufficient standard deviation (Whittemore & Kyriazakis, 2006). Repeatability, however, is too low to expect consistent uniformity values in successive litters. Damgaard *et al*. (2003) reported a repeatability of 0.17 in terms of standard deviation of birth weight, and this was confirmed by Quesnel *et al*. (2008). The modelling results of Sell-Kubiak *et al*. (2015a) suggest that the standard deviation (SD) of within-litter birth weight variation could be decreased by up to 10% after just one generation of selection, which is highly promising. An experiment in which birth weight uniformity was selected for in rabbits, also a highly prolific animal, showed a favourable response and positive results for the survival of the young (Quesnel *et al*., 2008).

An unfavourable genetic association has been found between maternal effect on piglet growth and litter heterogeneity. The variation in piglet birth weight has been found to be largely explained by maternal genetic effects, but through the progression of lactation, the direct genetic effect of the piglet became more important (Lundgren, 2011). Some factors such as genetic merit, oocyte quality, placental efficiency, and uterine capacity showed strong associations with uniformity, but underlying mechanisms responsible are still largely unknown. Foetal genotype does affect placental and endometrial vascularity during the final third of gestation, which affects homogeneity within the uterus (Yuan *et al*., 2015). Litter size, parity, sow birth date, and season at conception explained less than one fourth of variation in birth weight, and it is therefore assumed that a significant part of the heterogeneity is due to other factors such as embryo genotype, and epigenetic factors that affect the embryo and foetus development (Quesnel *et al*., 2008).

Considering the links between uniformity and other traits discussed earlier, there are possibilities for improving negative indicators of the trait. Piglet survival is strongly linked with uniformity, and can be improved through either direct selection, or selection on indicator traits (Rutherford *et al*., 2013). Selection for mothering ability might be an alternative option for improvement of piglet survival, even in varied litters. It has been suggested that an increase in (functional) teat number, improvement of milk yield and composition, and sow maternal behaviour could help negate the negative influences of competition within a litter to some extent (Rutherford *et al*., 2013). However, there is some evidence of undesirable correlations between teat number and other traits (Rutherford *et al*., 2013).

It may be possible to select for genetic ability of sows to increase their feed intake, especially during lactation, in order to raise litters more efficiently, and also improve post-lactational performance (Lundgren, 2011). LS5 has become a tool for genetic improvement of piglet survival while maintaining litter size improvement, as Danish breeders have shown success in this area (Nielsen *et al*., 2013; Putz *et al*., 2015; Yuan *et al*., 2015). It may be possible to select for improved uterine capacity to prevent IUGR and so decrease variation (Vallet *et al*., 2016; Wang *et al*., 2017). Birth weight in gilts was shown to be positively correlated with uterine length, which may help decrease IUGR, but uterine gland development, ovary size, and follicle number was not (Vallet *et al*., 2016). Dhakal *et al*. (2013), however, found that increases in uterine capacity increased birth weight, but failed to demonstrate any additive positive effects.

2.5. Conclusion

Pig production is an intensive industry which is highly subject to market changes, and must constantly strive to improve the efficiency of pork production. The continual increased selection emphasis on litter size has resulted in high levels of birth weight variation within a litter. Since it is not in the industry's best interest to decrease litter size, and postpartum management initiatives are variable and often ineffective, several studies deem genetic selection for lower birth weight variation a possible and relevant approach to improvement. Information regarding the causes, effects, and correlations of within-litter birth weight variation with other traits are relatively widely available, but adoption of litter uniformity into breeding objectives seems to be lacking. This may be due to its negative correlation with litter size, an important pillar of the industry, and so would be a costly exercise. There have also been no in-depth studies on litter uniformity in South Africa, so information relevant to the industry is lacking. This study will investigate levels of uniformity in three pig breeds on a stud facility under normal working conditions, as well as piglet performance later in life, in order to shed light on the practicality of including selection for within-litter birth weight uniformity in the South African industry.

Chapter 3: Materials and Methods

3.1 Introduction

Performance data and limited pedigree data from a number of sows and piglets (Table 3.1) was collected from a stud farm in order to evaluate birth weight uniformity as a predictor of future performance of piglets. As individual piglet measurements are not routinely recorded, a farmer who would be willing to participate had to be identified. The study was performed on a working farm as part of normal management practices, with addition individual measurements taken on all sows and piglets included in the study. The required data use consent by the Ethics Committee of the University of Pretoria was obtained (EC161021-077).

On-farm performance data of litters produced by purebred dams within their first three consecutive parities was included in this study. The birth weight uniformity (CVB) of the litter in which a piglet was born was compared with performance data at following points in their productive lives (21 day weight (21W), 28 day weight (28W), 70 day weight (70W)). The possible effect of birth weight uniformity, within and across breeds and parities, on future performance was investigated.

3.2 Materials

The data was provided by the stud farm, situated in the Limpopo province of South Africa, with the permission of both the farm and the South African Pork Producers Organisation (SAPPO). The farm personnel were trained to use a Standard Operating Protocol (Addendum A) used for data collection and were supervised for the first several collections. Stockmen were trained by the farm specifically for the house to which they were assigned, and were assigned to a specific room in each house. Staff were rotated, so a stockmen effect may be present.

A total of 119 females were included in the study, as shown in Table 3.1. Selection was random, from a pool of gilts of the appropriate breed on the stud farm. Females were approximately 30 weeks of age at first service, weighing approximately 135 kg. Records were taken for the first three parities of one selected group of sows, over 20 months. 119 females were used in parity one (40 Duroc, 39 Landrace, 40 Large White), producing 1327 piglets (371 Duroc, 471 Landrace, 485 Large White). Parity two included 75 of the original 119 females (24 Duroc, 28 Landrace, 23 Large White), producing 841 piglets (223 Duroc, 342 Landrace, 276 Large White). Parity three included 39 of the original females (7 Duroc, 16 Landrace, 16 Large White), producing 462 piglets (88 Duroc, 172 Landrace, 202 Large White). Timing of measurements are shown in Table 3.2. The data collection sheet template was included in Addendum A.

Table 3.1 Summary of records available for analysis per dam breed for each parity

Record		Dam Breed								
		Duroc			**Landrace**			**Large White**		
Parity		1	2	3	1	2	3	1	2	3
Number of dams		40	24	7	39	28	16	40	23	16
Number of piglets		371	223	88	471	342	172	485	276	202
Piglet Sex (%)	Boar	51.8	49.3	51.1	54.4	55.0	52.9	53.0	52.9	52.2
	Gilt	48.2	50.7	48.9	45.6	45.0	47.1	47.0	47.1	47.8
Foster Status (%)	NAT	77.9	87.0	54.5	85.1	93.6	89.5	88.2	85.9	77.1
	UNNAT	22.1	13.0	45.5	14.9	6.4	10.5	11.8	14.1	22.9
Sire Breed (%)	Duroc	84.1	78.5	64.8	4.0	16.7	44.2	2.7	4.7	30.3
	Landrace	1.1	7.2	0.0	14.0	45.6	14.0	79.2	40.6	41.8
	Large White	13.5	14.3	35.2	82.0	37.7	41.9	18.1	54.7	27.9
	Unknown	1.3	14.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0

NAT = piglet remained on birth dam, UNNAT = piglet taken off birth dam

The single farrowing house was divided into five separate, identical rooms, made up of three rows of seven identical farrowing pens. The farrowing house was mechanically ventilated using a negative pressure system, and a misting system for cooling. Each room contained litters of similar age, with each room managed under an all-in-all-out policy, and a sanitizing foot bath was placed at the entrance to every room. Each farrowing pen had a concrete floor and contained a farrowing crate, a waste grate, a nipple drinker, and a feed trough which was filled by an automatic dry feed dispensing system. Limited sawdust was placed in the pen for nesting behaviour and piglet comfort, as well as a heating lamp which was used up to two weeks average piglet age. All gilts/sows received the same feed, and piglets were offered dry feed from 14 days old. Piglets were not fostered to pens outside their room of birth. In this house, piglets were measured for individual birth weight within 12 hours after birth. Individual 21 day weight was measured every Wednesday, for piglets closest to the appropriate age, and individual 28 day weight was measured every Thursday, for piglets closest to the appropriate age.

Piglets were moved to the weaner house after weaning at approximately 28 days of age. The single weaner house was divided into five separate, identical rooms with concrete floors, made up of four rows of four identical pens. The house was subject to natural ventilation. Animals were separated into pens according to various factors, including size, and each pen contained 10 – 15 animals. Groups of undersized animals were put in pens fitted with heating lamps, which could have affected the performance of the piglets but could not be controlled due to the nature of an on-farm trial. Each room was managed under an all-in-all-out policy, and the entrance to every room had a sanitising foot bath. Every Monday, piglets closest to the appropriate age were measured for 70 day weight. Ten weeks is used as a weight of importance in this study, as it is the point at which pigs on the study farm are removed from the weaner house and moved into the testing phase to be selected for breeding, or slaughter (2017, Dr D. Visser, Pers. Comm., Juventis Genetrade, danie@juventis.co.za).

The recorded data included dam identification number, parity, dam breed, piglet identification number, piglet sex, sire breed, date of farrow, total number born, and number born alive. After scale calibration, individual birth weight, 21 day weight, 28 day weight, and 70 day weight were measured, as shown in Table 3.2. It was recorded at what point a piglet was deceased, and which piglets were fostered on and off. The dams were separated by breed so that uniformity, performance, and correlations could be compared between the Landrace (LR), Large White (LW), and Duroc (D). Data collection for this study began in September 2016, and the last data was collected in May 2018. First parity measurements occurred between September 2016 and July 2017, second parity between February 2017 and December 2017, and third parity between October 2017 and May 2018.

Table 3.2 Description of traits recorded in the study

Trait	Time of recording	Description
TNB	At cessation of farrow	Total number born per litter
NBA	At cessation of farrow	Number born alive per litter
BiW	Within 12 hours of birth	Individual piglet birth weight (kg)
21W	At approximately 3 weeks old	Individual 21 day piglet weight (kg)
28W	At approximately 4 weeks old	Individual 28 day piglet weight (kg)
70W	At approximately 10 weeks old	Individual 70 day piglet weight (kg)

TNB = total number born, NBA = number born alive, BiW = individual birth weight, 21W = individual 21 day weight, 28W = individual weaning weight, 70W = individual 10 week weight

3.3 Method

3.3.1 Data editing

A diagram showing the process for data collection is included in Addendum A. As the recording of individual piglet birth weight, 21 day weight, and 28 day weight were not part of the stud farm’s routine measurements for record keeping, it required additional labour and time on the part of farm personnel. Piglets were also not routinely tagged at birth, so routine was affected in order to identify individual piglets from birth. For 70 day weight, individual weights were only routinely recorded for purebred weaners. This would have significantly increased overall labour and time required by the personnel, possibly affecting the quality of recordings. However, the stud farm has since incorporated these measurements into their routine, due to their realised importance in selection.

In parity 1, a Landrace sow was removed due to incorrect data recorded. Therefore, 119 sows were included in the first parity, with one less Landrace sow than the other breeds. Between the sow’s first litter being weaned and the second farrow, 44 sows in the study were culled or sold. Of the data collected in parity 2, 4 sows were removed due to missing weight recordings. Therefore, 75 sows were included in the second parity analyses. Between the second litter weaning and the third farrow, a further 17 sows in the study were culled. Of the remaining sows, the data of 19 sows was not recorded. For the third parity analyses, 39 sows were therefore available.

Initial data editing required the conversion of piglet weights in order to make them comparable, as not all weights were taken at exactly the same age for every piglet, due to farm procedure. This was done by adjusting the weight according to the date of measurement, and using a calculated average daily gain (ADG). The table below contains an explanatory example (Table 3.3).

Table 3.3 Weight conversion explanatory example

	Birth weight	21 day weight	28 day weight	70 day weight
Recorded	A at 1 day	B at 19 days	C at 30 days	D at 65 days
Calculation	None	B – A = E	C – B = H	D – C = K
		E/19 = F	H/(30-19) = I	K/(65-30) = L
		F*21 = G	I*28 = J	L*70 = M
Converted	A	G	J	M

Due to cross-fostering, piglets used in the study were not always from a dam used in the study. Litters that were not born to dams being studied often did not have their individual weights measured, only overall litter weight. When a piglet from one of these litters was fostered onto a dam in the study without a birth weight, their weights were allocated by taking the average individual weight from the litter they were born into. Prefixes of W, D, or L, were added to duplicate piglet ID numbers, according to breed, to ensure unique piglet ID numbers. Fostering status was edited such that those fostered in or out were grouped as “UNNAT” in the analyses, versus those that were born of a study dam and remained in her care labeled as “NAT.” In order to make statistical analysis simpler, season of birth and year of birth for piglets was nested into a single effect, titled season(year). In parity 1, summer ran from 2016 into 2017. As such, the same season was included as two separate effects due to the change in year.

3.3.2 Statistical analysis

The statistical software SAS 9.4 (SAS, 2018) was used to perform the statistical analyses. The analyses were performed with the assistance of a research assistant from the Department of Statistics of the University of Pretoria. Descriptive statistics were calculated for all three parities, using the univariate procedure, for the dependent variables, which were TNB, NBA, BiW, CVB, 21W, 28W, and 70W. These were separated by dam breed. Pearson correlation coefficients were calculated for all three parities to investigate whether low BiW carried through to low 70W, if CVB affected weaning mortality rate, and if lower CVB led to better performance (resulting in higher 21W, 28W, 70W).

General linear models (GLM) were performed for parity 1, 2, and 3. Models were fitted to compare weights at birth, 21 days, 28 days, and 70 days, across a number of fixed effects, and level of significance used was 0.05. The data was first explored separately for each parity, then across parities. The general linear model used in the analyses can be expressed as:

$$y_{ij} = \mu + \beta_i + e_{ij}$$

Where y_{ij} = performance record j for fixed effect i

μ = piglet mean

β_i = i^{th} fixed effect contributing to variation (parity, dam breed, sire breed, piglet sex, year and season of piglet birth, farrowing room, weaning room, interactions)

e_{ij} = random error for performance record j for the i^{th} effect

The fixed effects to be tested were parity, piglet sex, dam breed, sire breed, dam parity, year and season of piglet birth, farrowing room, weaning room, and various interaction effects. The Type III Sum of Squares F-values and p-values were interpreted to test whether mean values of the dependent variable (e.g. birth weight) differed significantly across the fixed effects. The level of significance used was $\alpha=0.05$. Since the data was not balanced, multiple comparisons of the dependent variables across the fixed effects were evaluated by Least Square Means (LSM). The p-values were adjusted by the Scheffe adjustment. Lastly, the data for the two parities were combined into one data set and parity was analysed as an additional effect.

Chapter 4: Results

This study aimed to investigate whether birth weight uniformity was a useful predictor of future performance in piglets. Due to the literature surrounding the topic, higher litter uniformity was hypothesized to have a positive impact upon piglet performance. Additional performance traits were also analysed, as they are important in attaining breeding objectives. Dams from the three major breeds, Duroc, Landrace, and Large White, were included and recorded over three parities, and the performance of their piglets was measured. The results are separated into parity 1, 2, and 3, followed by a cross-parity analysis.

4.1 Results for parity 1

Non-genetic effects on performance traits are reported in Table 4.1. NBA was affected ($p < 0.05$) by all tested effects except sex, while other traits were only affected by one or two variables. In Table 4.2, the descriptive statistics have been summarised for the first parity according to the breed of dam. Litter size (TNB and NBA) was significantly different ($p < 0.05$) between all dam breeds, Duroc dams producing the smallest litters in parity 1. Duroc dam's piglets had a significantly higher average birth weight, Duroc and Large White dam piglets were largest at 3 weeks and weaning, and Large White piglets were larger at 70 days ($p < 0.05$). Landrace dam's litters had the lowest within-litter birth weight variation ($p < 0.05$), and all breed's survival rates to weaning were similar ($p > 0.05$).

Table 4.1 Type III Sum of Squares significance for each performance trait per fixed effect in parity 1

Variable	Trait							
	TNB	**NBA**	**BiW**	**21W**	**28W**	**70W**	**CVB**	**SURV**
Sex	0.86	0.99	*	0.09	0.35	0.72	0.39	0.18
Dam breed	**	**	0.35	0.47	0.29	0.31	**	0.06
Sire breed	**	**	*	0.51	0.26	*	0.94	*
Season	0.10	**	0.17	0.35	**	**	0.97	0.22
Farrow room	NT	NT	NT	**	**	NT	NT	**
Wean room	NT	NT	NT	NT	NT	*	NT	NT
Foster status	NT	NT	NT	**	0.74	0.21	NT	*
Dam breed x Sire breed	**	**	0.08	0.17	0.38	**	*	0.28

NBA = number born alive, TNB = total number born, BiW = individual birth weight, 21W = individual 21 day weight, 28W = individual 28 day weight, 70W = individual 70 day weight, CVB = coefficient of variation for birth weight, SURV = survival to weaning, NT = Not tested

**p <0.01; *p <0.05; actual significance for p >0.05

Sex of the piglet (Addendum B) had an effect upon its birth weight, boars being significantly larger than gilts ($p < 0.05$). Piglets that were kept with their natural dam had a higher survival rate to weaning, but a lower 21W ($p < 0.05$) compared to fostered piglets.

Table 4.2 Descriptive statistics of performance traits per dam breed for parity 1

Variable		Dam Breed		
		Duroc	**Landrace**	**Large White**
TNB	N	364	443	455
	Mean	9.33^{c}	11.36^{b}	11.38^{a}
	Minimum	2.00	2.00	6.00
	Maximum	15.00	21.00	17.00
	CV	33.73	34.66	20.27
NBA	N	339	425	433
	Mean	8.69^{c}	10.90^{b}	10.83^{a}
	Minimum	2.00	2.00	6.00
	Maximum	15.00	19.00	16.00
	CV	41.16	36.33	20.80
BiW (kg)	N	371	471	485
	Mean	1.54^{a}	1.38^{b}	1.35^{c}
	SE	0.02	0.01	0.01
	Minimum	0.60	0.60	0.60
	Maximum	2.40	2.10	2.20
	CV	19.66	20.34	22.66
21W (kg)	N	315	413	438
	Mean	4.95^{a}	4.75^{b}	5.06^{a}
	SE	0.06	0.06	0.06
	Minimum	1.20	1.50	1.40
	Maximum	7.40	8.10	9.20
	CV	22.70	26.60	26.21
28W (kg)	N	310	407	431
	Mean	6.46^{a}	6.21^{b}	6.47^{a}
	SE	0.08	0.08	0.08
	Minimum	2.10	2.10	2.00
	Maximum	11.60	12.60	10.90
	CV	22.35	25.92	24.91
70W (kg)	N	158	226	221
	Mean	24.07^{b}	24.24^{b}	25.13^{a}
	SE	0.42	0.35	0.34
	Minimum	6.90	9.50	6.20
	Maximum	37.10	37.70	37.40
	CV	22.17	21.99	20.30
CVB	N	40	39	40
	Mean	16.66^{c}	15.65^{b}	17.56^{a}
	SE	0.33	0.27	0.16
	Minimum	6.66	4.80	10.20
	Maximum	31.05	31.42	25.38
	CV	37.27	37.55	18.90
SURV (%)	N	40	39	40
	Mean	0.88^{a}	0.90^{a}	0.90^{a}
	SE	0.01	0.01	0.05
	Minimum	0.38	0.09	0.67
	Maximum	1.00	1.00	1.00
	CV	17.27	12.56	10.67

NBA = number born alive, TNB = total number born, BiW = individual birth weight, 21W = individual 21 day weight, 28W = individual 28 day weight, 70W = individual 70 day weight, N = number of observations, SE = standard error, SD = standard deviation, CV = coefficient of variation, CVB = coefficient of variation of birth weight, SURV = survival to weaning

$^{a, b, c}$ – Denote significant differences between means within performance traits in rows ($p < 0.05$)

In Table 4.3, the results for parental breed as an effect are shown. Dam breed was found to only significantly affect TNB, NBA, and CVB. When Large Whites were used as the sire breed, litter size (TNB and NBA) was significantly larger, and survival to weaning was higher ($p < 0.05$). Duroc sires produced litters with the largest birth weight, while Landrace sires produced piglets with the highest weight at 70 days ($p < 0.05$).

Table 4.3 LS Means ±SE depicting the influence of parental breed on performance traits for parity 1

Trait		Parental breed	
		Dam	
	Duroc	**Landrace**	**Large White**
TNB	10.43±0.15^{c}	12.65±0.14^{a}	12.11±0.13^{b}
NBA	9.72±0.15^{c}	12.24±0.13^{a}	11.18±0.13^{b}
CVB	16.55±0.22^{b}	15.65±0.19^{c}	17.56±0.19^{a}
		Sire	
	Duroc	**Landrace**	**Large White**
TNB	10.31±0.16^{c}	11.59±0.14^{b}	12.64±0.13^{a}
NBA	9.67±0.15^{c}	11.04±0.13^{b}	12.28±0.12^{a}
BiW (kg)	1.55±0.02 ^{a}	1.36±0.01 ^{b}	1.37±0.01 ^{b}
70W (kg)	23.84±0.29^{b}	24.86±0.24^{a}	24.44±0.24^{ab}
SURV (%)	0.87± 0.01^{b}	0.89±0.00^{b}	0.91±0.00^{a}

NBA = number born alive, CVB = coefficient of variation of piglet birth weight, TNB = total number born, BiW = individual birth weight, 70W = individual 70 day weight, SURV = survival to weaning

$^{a, b, c}$ – Denote significant differences between means within fixed effects in rows ($p <0.05$)

Farrowing house effects can be found in the addendum B. Room D housed significantly larger piglets than room B at 21 days, and room B housed smaller piglets than room D at 28 days ($p < 0.05$). As shown in the Addendum B, weaning room C (26.08±0.33, $p < 0.05$) housed the significantly larger piglets at 70 days, and room E (22.67±0.38, $p < 0.05$) the significantly smaller piglets, room A housing middle-range sized piglets (24.21±0.30, $p < 0.05$). The season and year in which a piglet was born had a significant effect upon NBA, 28W, and 70W, as shown in Table 4.4. Farrowings in summer of 2016 and autumn of 2017 produced the highest NBA ($p < 0.05$). The highest weaning weight was produced when piglets were farrowed in spring 2016 and summer 2017, while the lowest 70 day weight was attained by piglets farrowed in spring 2016 ($p < 0.05$.

Table 4.4 LS means ±SE depicting the influence of period of birth on performance traits for parity 1

Trait	2016		2017	
	Spring	Summer	Summer	Autumn
NBA	11.01±0.14^{bc}	11.54±0.16^{ab}	10.61±0.13^{c}	12.07±0.19^{a}
28W (kg)	6.48±0.04^{a}	5.76±0.05^{c}	6.59±0.03^{a}	6.09±0.05^{b}
70W (kg)	23.10±0.25^{c}	24.99±0.35^{ab}	25.90±0.30^{a}	24.54±0.32^{b}

NBA = number born alive, 28W = individual 28 day weight, 70W = individual 70 day weight

$^{a, b, c}$ – Denote significant differences between means within fixed effects in rows ($p <0.05$)

Table 4.1.5 illustrates the interaction effect between dam breed and sire breed upon the performance of the piglet. TNB was lower when Durocs were used and higher when two white breeds are used, and Duroc sires bred with Duroc or Large White dams produced the lowest NBA, and Landrace bred with Large White the highest ($p < 0.05$). Uniformity appears to be significantly highest in a pure Duroc litter, on average, but weight at 70 days the lowest ($p < 0.05$).

Table 4.5 LS means ±SE depicting the influence of dam breed x sire breed interaction on performance traits for parity 1

Trait	Duroc dam			Landrace dam			Large White dam		
	Duroc sire	Landrace sire	Large White sire	Duroc sire	Landrace sire	Large White sire	Duroc sire	Landrace sire	Large White sire
TNB	10.24 ±0.17^{c}	13.00± 1.47	11.42 ±0.42	10.58 ±0.68	11.15 ±0.36^{bc}	13.01 ±0.15^{a}	9.62 ±0.82^{bc}	12.01 ±0.15^{b}	12.93 ±0.31^{ab}
NBA	9.63 ±0.16^{c}	12.25± 1.43	11.28 ±0.40	10.37 ±0.65	10.61 ±0.35^{bc}	12.62 ±0.15^{a}	9.46 ±0.79^{abc}	11.45 ±0.15^{b}	12.76 ±0.30^{ab}
CVB	16.74 ±0.24^{ab}	17.64 ±2.41	14.84 ±0.58^{cb}	8.02 ±0.94^{d}	13.98 ±0.50^{c}	16.32 ±0.21^{b}	16.94 ±1.13^{abc}	17.88 ±0.21^{a}	16.23 ±0.44^{abc}
70W	23.91 ±0.30	NT	30.30 ±3.51	19.00 ±1.57^{a}	22.58 ±0.58^{a}	24.58 ±0.27^{ac}	26.56 ±1.57^{ac}	25.34 ±0.27^{bc}	23.75 ±0.54^{ac}

NBA = number born alive, TNB = total number born, CVB = coefficient of variation of piglet birth weight, 70W = individual 70 day weight (kg), NT = Not tested

$^{a, b, c}$ – Denote significant differences between means within fixed effects in rows ($p < 0.05$)

Pearson correlation scatter plots that are not included in this chapter can be found in Addendum B. Within-litter birth weight variation was only lowly correlated (below 0.20) with birth weight (negative), TNB, and NBA (positive) ($p < 0.01$). NBA was moderately negatively (-0.31) correlated with birth weight (Figure 4.1), and lowly negatively correlated with 21W (-0.15) and 28W (-0.14) ($p < 0.01$).

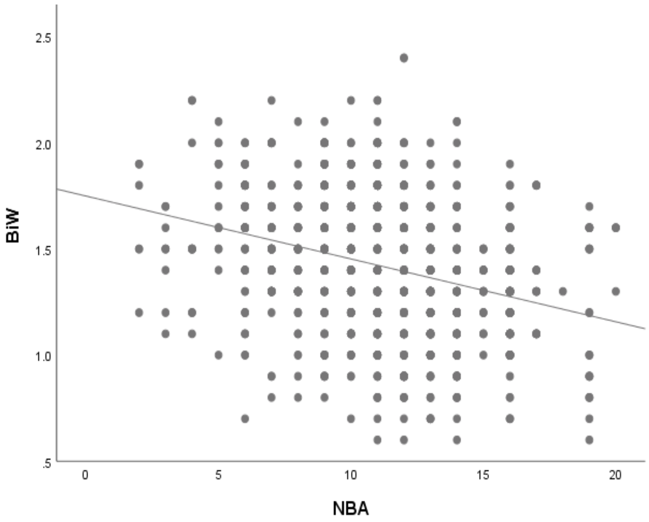

Figure 4.1 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between number born alive (NBA) and individual birth weight (BiW) for parity 1 ($R^2 = 0.093$)

The correlation between birth weight and weight at 28 days (0.42) was moderately positive (Figure 4.2), as well as with weight at 21 days (0.44), and 70 days (0.35) (Figure 4.3) ($p < 0.01$).

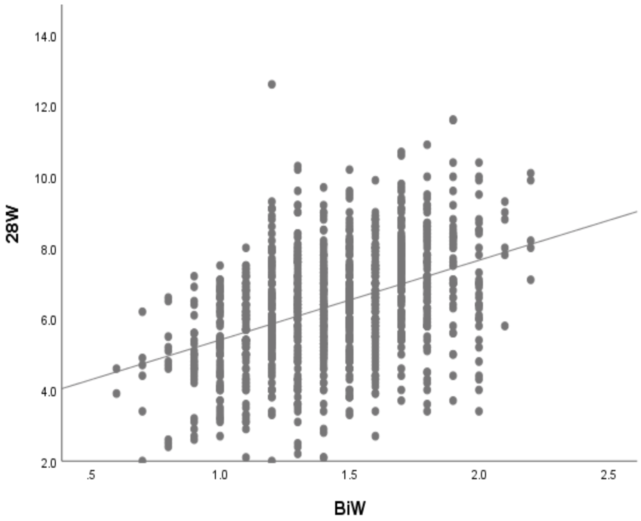

Figure 4.2 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between individual weaning weight (28W) and individual birth weight (BiW) for parity 1 ($R^2 = 0.175$)

Weight at 21 days was highly positive correlated with weight at weaning (0.88) and at 70 days (0.57), and weaning weight was highly correlated with weight at 70 days (0.61) ($p < 0.01$). Survival to weaning was not meaningfully correlated to any other trait.

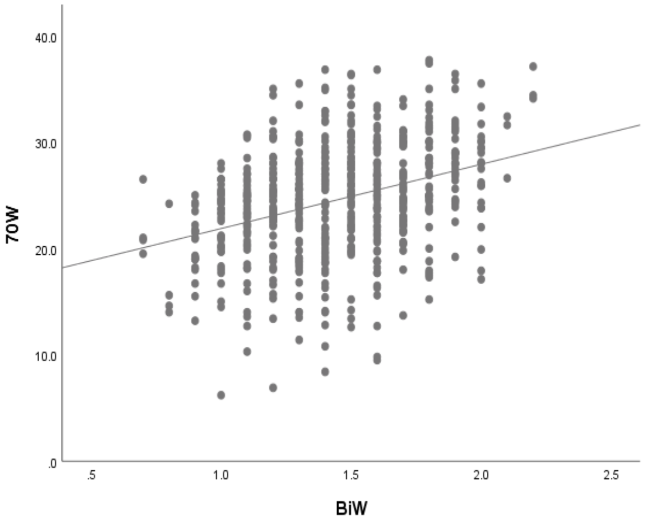

Figure 4.3 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between individual 70 day weight (70W) and individual birth weight (BiW) for parity 1 ($R^2 = 0.123$)

4.2 Results for parity 2

Table 4.6 reports the significance of the variable effects on the performance traits. TNB, NBA, and CVB were significantly ($p < 0.05$) affected by nearly all tested effects, while other traits showed several effects were statistically insignificant ($p > 0.05$). In Table 4.7, the descriptive statistics are summarized for parity 3. The litter size (TNB and NBA) are significantly ($p < 0.05$) smaller for Duroc dams, and white breeds are similar to one another. The birth weight for litters of Large White dams is significantly smaller, while the 21 and 28 day weights are similar for all three breeds of dam. Landrace dams produced litters with the lowest weight at 70 days, but the highest survival rate to weaning, and within-litter birth weight variation was similar for all three breeds ($p < 0.05$).

Table 4.6 Type III Sum of Squares significance for each performance trait per fixed effect in parity 2

Variable	Trait							
	TNB	**NBA**	**BiW**	**21W**	**28W**	**70W**	**CVB**	**SURV**
Sex	0.88	0.29	**	**	0.27	0.63	0.58	0.55
Dam breed	**	**	*	0.84	0.64	*	**	**
Sire breed	**	**	0.12	0.61	0.75	*	**	*
Season	**	**	0.60	*	**	0.31	**	0.90
Farrow room	NT	NT	NT	0.86	0.59	NT	NT	**
Wean room	NT	NT	NT	NT	NT	0.60	NT	NT
Foster status	NT	NT	NT	0.48	0.43	0.06	NT	0.38
Dam breed x Sire breed	**	**	*	0.54	0.56	0.96	**	**

NBA = number born alive, TNB = total number born, BiW = individual birth weight, 21W = individual 21 day weight, 28W = individual 28 day weight, 70W = individual 70 day weight, CVB = coefficient of variation for birth weight, SURV = survival to weaning, NT = Not tested

**p <0.01; *p <0.05; actual significance for p >0.05

The sex of the piglet (Addendum C) affected both BiW and 21W, boars reaching higher weights for both ($p < 0.05$). Farrowing room (Addendum C) was shown to affect survival rate, such that survival to weaning was found to be lower in rooms A and E ($p < 0.05$).

Table 4.7 Descriptive statistics of performance traits per dam breed for parity 2

Variable		Dam Breed		
		Duroc	**Landrace**	**Large White**
TNB	N	226	340	281
	Mean	9.42^{b}	12.14^{a}	12.22^{a}
	Minimum	3	7	6
	Maximum	15	20	19
	CV	30.02	24.21	28.99
NBA	N	213	329	258
	Mean	8.88^{b}	11.75^{a}	11.22^{a}
	Minimum	2	6	4
	Maximum	12	19	18
	CV	29.60	24.69	34.94
BiW (kg)	N	223	342	276
	Mean	1.64^{a}	1.62^{a}	1.41^{b}
	SE	0.02	0.02	0.02
	Minimum	0.70	0.20	0.70
	Maximum	2.50	2.90	2.90
	CV	21.27	23.17	25.62
21W (kg)	N	197	330	246
	Mean	5.76^{a}	5.66^{a}	5.61^{a}
	SE	0.09	0.06	0.10
	Minimum	1.2	1.40	1.80
	Maximum	9.00	9.00	9.40
	CV	23.09	20.56	28.29
28W (kg)	N	195	325	241
	Mean	7.52^{a}	7.28^{a}	7.30^{a}
	SE	0.12	0.08	0.12
	Minimum	3.40	3.60	2.00
	Maximum	12.70	11.20	12.70
	CV	21.79	18.89	25.64
70W (kg)	N	112	244	154
	Mean	26.13^{a}	21.62^{b}	24.77^{a}
	SE	0.48	0.37	0.53
	Minimum	14.00	8.00	6.00
	Maximum	35.80	32.50	41.00
	CV	19.45	26.51	26.52
CVB	N	25	28	23
	Mean	17.34^{a}	17.72^{a}	17.95^{a}
	SE	0.58	0.4	0.34
	Minimum	6.69	7.58	3.99
	Maximum	43.72	39.53	32.90
	CV	49.63	41.38	31.89
SURV (%)	N	25	28	23
	Mean	0.90^{b}	0.95^{a}	0.89^{b}
	SE	0.01	0.00	0.01
	Minimum	0.44	0.80	0.62
	Maximum	1.00	1.00	1.00
	CV	14.57	6.22	12.14

NBA = number born alive, TNB = total number born, BiW = individual birth weight, 21W = individual 21 day weight, 28W = individual 28 day weight, 70W = individual 70 day weight, N = number of observations, SE = standard error, SD = standard deviation, CV = coefficient of variation, CVB = coefficient of variation of birth weight, SURV = survival to weaning

$^{a, b, c}$ – Denote significant differences between means within performance traits in rows ($p < 0.05$)

Table 4.8 illustrates the effect of parental breed on performance traits of the piglets. Dam breed significantly ($p < 0.05$) affected all traits except 21 and 28 day weights. Litter size was smaller for Duroc dams and sires, variation in birth weight was lowest for Duroc dams, and birth weight was largest for these dams ($p < 0.05$). The Landrace dams and sires produced litters with the lowest weight at 70 days, and highest survival rate to weaning ($p < 0.05$). Large White sires produced the highest birth weight variation of the sire breeds ($p < 0.05$).

Table 4.8 LS Means ±SE depicting the influence of parental breed on performance traits for parity 2

Trait	Parental breed		
		Dam	
	Duroc	**Landrace**	**Large White**
TNB	10.33±0.17^{b}	12.87±0.14^{a}	13.16±0.16^{b}
NBA	9.81±0.18^{b}	12.49±0.14^{a}	12.42±0.16^{a}
BiW (kg)	1.64±0.02^{a}	1.62±0.02^{ac}	1.41±0.02^{c}
CVB	17.34±0.37^{c}	17.72±0.30^{b}	17.95±0.33^{a}
70W (kg)	26.13±0.42^{a}	21.60±0.28^{c}	24.75±0.36^{b}
SURV (%)	0.88±0.00^{b}	0.95±0.00^{a}	0.88±0.00^{b}
		Sire	
	Duroc	**Landrace**	**Large White**
TNB	10.79±0.16^{c}	11.89±0.15^{b}	13.83±0.15^{a}
NBA	10.27±0.17^{c}	11.38±0.16^{b}	13.26±0.15^{a}
CVB	16.87±0.35^{b}	17.32±0.33^{b}	18.68±0.31^{a}
70W (kg)	25.00±0.36^{a}	21.98±0.33^{b}	23.92±0.33^{a}
SURV (%)	0.90±0.00^{b}	0.92±0.00^{a}	0.91±0.00^{b}

TNB = total number born, NBA = number born alive, BiW = individual birth weight, CVB = coefficient of variation for birth weight, 70W = individual 70 day weight, SURV = survival to weaning

$^{a, b, c}$ – Denote significant differences between means within fixed effects in rows ($p <0.05$)

Litters farrowed in autumn 2017 were the smallest litters, and summer farrows produced the largest, however spring farrows produced the lowest variation in birth weight ($p < 0.05$) (Table 4.9). Piglets farrowed in spring had the largest weight at 21 and 28 days of age ($p < 0.05$).

Table 4.9 LS means ±SE depicting the influence of period of birth on performance traits for parity 2

Trait	2017			
	Spring	Summer	Autumn	Winter
TNB	12.26±0.35^{ab}	13.38±0.30^{a}	11.86±0.13^{b}	12.58±0.14^{a}
NBA	11.37±0.36^{bc}	13.14±0.31^{a}	11.31±0.13^{c}	12.04±0.15^{b}
CVB	11.90±0.75^{c}	18.52±0.65^{ab}	17.04±0.28^{b}	19.27±0.31^{a}
21W (kg)	6.24±0.16^{a}	5.79±0.14^{ab}	5.59±0.06^{b}	5.62±0.07^{b}
28W (kg)	7.89±0.19^{a}	7.61±0.18^{ab}	7.18±0.08^{b}	7.33±0.08^{b}

TNB = total number born, NBA = number born alive, CVB = coefficient of variation for birth weight, 21W = individual 21 day weight, 28W = individual 28 day weight

$^{a, b, c}$ – Denote significant differences between means within fixed effects in rows (p <0.05)

Parental breed crosses as an effect is reported in table 4.10. Large White sires bred with white dams produced the largest litter sizes, while the smallest birth weight was produced by Duroc sires bred with a Landrace dam, and Large White purebred piglets (p < 0.05). The lowest variation in birth weight was produced by crosses of a white dam with a Duroc sire. Duroc dams produced significantly different survival rates in their litters when crossed with each sire breed, with the Landrace sire showing the lowest piglet survival rate (p < 0.05).

Table 4.10 LS means ±SE depicting the influence of dam breed x sire breed interaction on performance traits for parity 2

Trait	Duroc dam			Landrace dam			Large White dam		
	Duroc sire	Landrace sire	Large White sire	Duroc sire	Landrace sire	Large White sire	Duroc sire	Landrace sire	Large White sire
TNB	10.39 ±0.19^{b}	10.38 ±0.64^{bc}	9.94 ±0.46^{b}	11.75 ±0.34^{bd}	12.54 ±0.21^{cd}	13.75 ±0.23^{a}	11.85 ±0.71^{acd}	11.21 ±0.24^{b}	14.73 ±0.21^{a}
NBA	9.87 ±0.20^{c}	9.50 ±0.66^{bc}	9.63 ±0.46^{c}	11.23 ±0.35^{bc}	12.17 ±0.21^{b}	13.42 ±0.23^{a}	11.38 ±0.73^{abc}	10.54 ±0.25^{c}	13.90 ±0.21^{a}
BiW (kg)	1.62 ±0.02^{ac}	1.59 ±0.08	1.78 ±0.06^{a}	1.69 ±0.04^{a}	1.65 ±0.03^{a}	1.55 ±0.03^{ac}	1.28 ±0.09^{bc}	1.57 ±0.03^{ac}	1.30 ±0.03^{b}
CVB	17.70 ±0.42	13.92 ±1.38	17.06 ±0.97	14.91 ±0.73^{b}	17.60 ±0.44^{ab}	19.12 ±0.48^{a}	14.33 ±0.53^{ab}	17.42 ±0.52^{ab}	18.64 ±0.45^{a}
SURV (%)	0.88 ±0.01^{b}	0.77 ±0.02^{c}	0.97 ±0.01^{a}	0.96 ±0.01^{a}	0.96 ±0.01^{a}	0.93 ±0.01^{a}	0.91 ±0.02^{ab}	0.89 ±0.01^{b}	0.87 ±0.01^{b}

TNB = total number born, NBA = number born alive, BiW = individual birth weight, CVB = coefficient of variation for birth weight, SURV = survival to weaning

$^{a, b, c}$ – Denote significant differences between means within fixed effects in rows (p <0.05)

Pearson correlation scatter plots that are not shown here can be found in Addendum C. CVB was lowly positively correlated with birth weight (0.19) and NBA (0.10) ($p < 0.01$). NBA was moderately negatively correlated with birth weight (-0.32) (Figure 4.4) and weight at 70 days (-0.24) ($p < 0.01$).

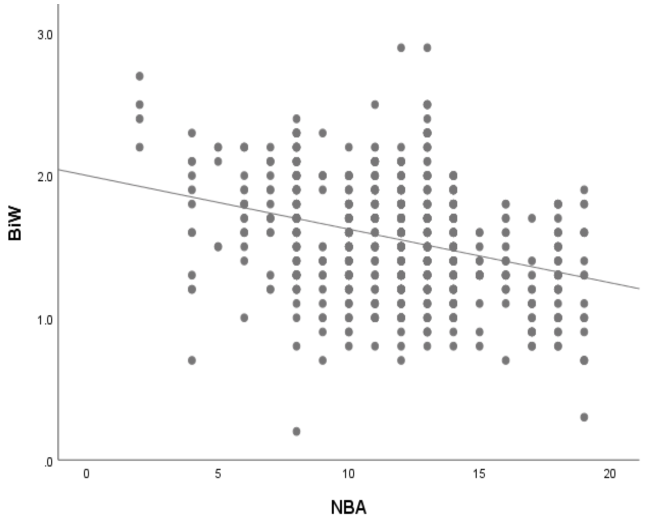

Figure 4.4 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between number born alive (NBA) and individual birth weight (BiW) for parity 2 ($R^2 = 0.101$)

Birth weight was moderately positively correlated with weaning weight (0.45) (Figure 4.5) and survival to weaning (0.18) ($p < 0.01$). Weaning weight was lowly positively correlated with weight at 70 days (0.19) ($p < 0.01$).

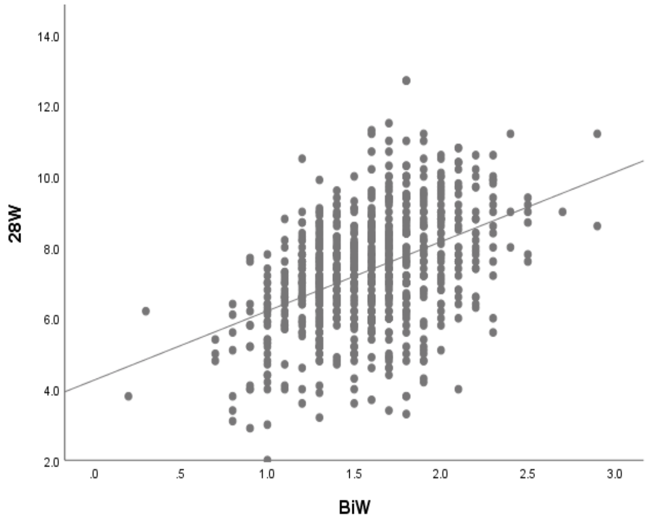

Figure 4.5 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between individual weaning weight (28W) with individual birth weight (BiW) for parity 2 ($R^2 = 0.199$)

4.3 Results for parity 3

Table 4.11 summarises the descriptive statistics for parity 3. TNB and 70 day weight was not measured in parity 3, due to operational limitations on-farm.

Table 4.11 Descriptive statistics of performance traits per dam breed for parity 3

Variable		Dam Breed		
		Duroc	**Landrace**	**Large White**
NBA	N	88	172	202
	Mean	13.09^{a}	12.20^{b}	12.80^{ab}
	SE	0.28	0.22	0.17
	Minimum	9	2	7
	Maximum	17	16	18
	CV	19.68	23.93	18.36
BiW	N	88	172	202
	Mean	1.54^{b}	1.71^{a}	1.48^{b}
	SE	0.04	0.51	0.03
	Minimum	0.60	0.80	0.60
	Maximum	2.40	2.90	2.40
	CV	25.54	22.55	24.31
21W (kg)	N	69	151	177
	Mean	5.85^{a}	5.48^{a}	5.15^{a}
	SE	0.22	0.11	0.12
	Minimum	1.40	1.40	1.20
	Maximum	9.80	9.50	9.80
	CV	31.13	25.18	28.84
28W (kg)	N	65	143	176
	Mean	7.72^{a}	7.08^{a}	7.33^{a}
	SE	0.25	0.15	0.16
	Minimum	1.80	2.0	1.40
	Maximum	12.60	11.70	14.40
	CV	25.90	25.06	28.1
CVB	N	7	16	16
	Mean	24.13^{a}	16.25^{c}	20.32^{b}
	SE	0.67	0.40	0.31
	Minimum	17.80	3.14	12.26
	Maximum	39.81	25.59	28.13
	CV	26.17	32.15	21.51
SURV (%)	N	7	16	16
	Mean	0.80^{c}	0.94^{a}	0.90^{b}
	SE	0.02	0.01	0.01
	Minimum	0.43	0.14	0.14
	Maximum	1.00	1.00	1.00
	CV	23.65	16.96	12.08

NBA = number born alive, BiW = individual birth weight, 21W = individual 21 day weight, 28W = individual 28 day weight, N = number of observations, SE = standard error, SD = standard deviation, CV = coefficient of variation, CVB = coefficient of variation of birth weight, SURV = survival to weaning

$^{a, b, c}$ – Denote significant differences between means within performance traits in rows ($p < 0.05$)

Litter size was highest for the Duroc dams, and Landrace dams produced piglets that were heavier at birth ($p < 0.05$), while weights at 21 and 28 days were similar for piglets from all three breeds ($p > 0.05$) (Table 4.11). Landrace dams produced litters with the highest uniformity at birth and the highest survival rate to weaning. In parity 3 (Table 4.12), survival rate to weaning and variation in birth weight were affected by all effects measured, while other traits were only affected by one or two variables ($p < 0.05$).

Table 4.12 Type III Sum of Squares significance for each performance trait per fixed effect in parity 3

Variable	Trait					
	NBA	**BiW**	**21W**	**28W**	**CVB**	**SURV**
Sex	0.29	0.09	0.33	0.05	0.82	1.00
Dam breed	0.12	**	0.78	0.61	**	*
Sire breed	*	0.37	0.62	0.54	*	**
Season	**	*	0.24	0.48	**	**
Farrow room	NT	NT	**	**	NT	*

NBA = number born alive, TNB = total number born, BiW = individual birth weight, 21W = individual 21 day weight, 28W = individual 28 day weight, CVB = coefficient of variation for birth weight, SURV = survival to weaning, NT = Not tested

**$p <0.01$; *$p <0.05$; actual significance for $p >0.05$

In Table 4.13, the effect of parental breed is reported. Birth weight was highest in piglets of Landrace dams while variation was lowest, and survival to weaning was lowest in litters from Duroc dams ($p < 0.05$). NBA for all three sire breeds was similar ($p > 0.05$). Birth weight uniformity was lowest in litters from Large White sires, and survival to weaning was lowest for litters from Duroc sires ($p < 0.05$).

Table 4.13 LS Means ±SE depicting the influence of parental breed on performance traits for parity 3

Trait	Parental breed		
		Dam	
	Duroc	**Landrace**	**Large White**
BiW (kg)	$1.54±0.04^b$	$1.71±0.03^a$	$1.48±0.03^b$
CVB	$24.13±0.49^a$	$16.25±0.35^c$	$20.32±0.32^b$
SURV (%)	$0.79±0.02^b$	$0.92±0.01^a$	$0.90±0.01^a$
		Sire	
	Duroc	**Landrace**	**Large White**
NBA	12.34±0.21	12.75±0.18	12.78±0.22
CVB	$20.17±0.39^a$	$20.28±0.33^a$	$17.71±0.41^b$
SURV (%)	$0.83±0.01^b$	$0.92±0.01^a$	$0.90±0.01^a$

TNB = total number born, NBA = number born alive, BiW = individual birth weight, CVB = coefficient of variation for birth weight, 70W = individual 70 day weight, SURV = survival to weaning

$^{a, b, c}$ – Denote significant differences between means within fixed effects in rows ($p <0.05$)

Table 4.14 shows that autumn farrows produced the lowest NBA, but similar to summer, while the heaviest piglets at birth were born in summer ($p < 0.05$). Birth weight uniformity was lowest in autumn, and survival to weaning increased from spring births to autumn births ($p < 0.05$).

Table 4.14 LS means ±SE depicting the influence of period of birth on performance traits for parity 3

Trait	2017		
	Spring	Summer	Autumn
NBA	13.26±0.16^{a}	11.93±0.18^{b}	11.53±0.65^{b}
BiW (kg)	1.53±0.02^{b}	1.65±0.03^{a}	1.29±0.10^{b}
CVB	21.11±0.29^{b}	17.38±0.33^{b}	21.72±1.19^{a}
SURV (%)	0.74±0.04^{c}	0.85±0.01^{b}	0.94±0.01^{a}

NBA = number born alive, BiW = individual birth weight, CVB = coefficient of variation for birth weight, SURV = survival to weaning

$^{a, b, c}$ – Denote significant differences between means within fixed effects in rows ($p < 0.05$)

Room E housed the lightest piglets at 21 days and 28 days, while survival to weaning was similar ($p > 0.05$) in all rooms (Table 4.15).

Table 4.15 LS means ±SE depicting the influence of farrowing room on performance traits for parity 3

Trait	Farrowing Room				
	A	B	C	D	E
21W (kg)	5.89±0.17^{ab}	5.33±0.15^{b}	5.75±0.15^{ab}	6.14±0.18^{a}	4.48±0.20^{c}
28W (kg)	7.88±0.22^{a}	7.17±0.19^{a}	7.32±0.20^{a}	7.98±0.23^{a}	5.98±0.25^{b}
SURV (%)	0.86±0.02	0.88±0.01	0.91±0.01	0.88±0.02	0.93±0.02

21W = individual 21 day weight, 28W = individual 28 day weight, SURV = survival to weaning

$^{a, b, c, d}$ – Denote significant differences between means within fixed effects in rows ($p < 0.05$)

Pearson correlation scatter plots that were not included here can be found in Addendum D. NBA was moderately negatively correlated with birth weight (-0.30), and lowly correlated with survival to weaning (-0.25), within-litter birthweight variation (-0.23) and weaning weight (-0.11) ($p < 0.01$).

Birth weight was highly positively correlated with weight at 21 days (0.54) and 28 days (0.51) (Figure 4.6), moderately negatively correlated with CVB (-0.34), and lowly positively correlated with survival to weaning (0.15) ($p < 0.01$).

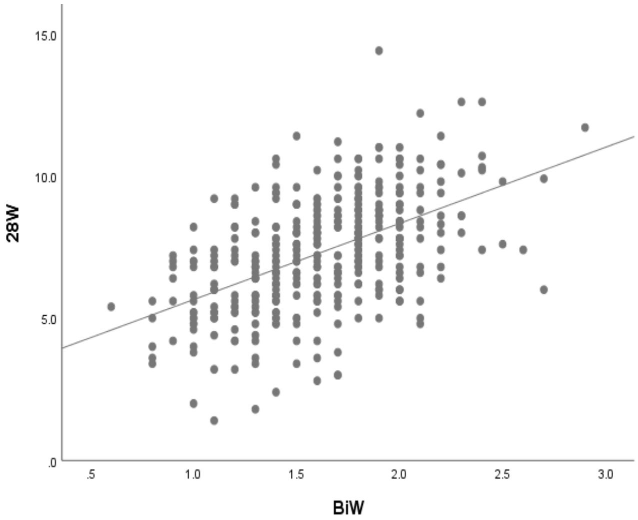

Figure 4.6 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between individual weaning weight (28W) and individual birth weight (BiW) for parity 3 ($R^2 = 0.264$)

CVB was lowly negatively correlated with survival to weaning (-0.21), and weight at 21 days was highly positively correlated with weaning weight (0.95) ($p < 0.01$), found in Addendum D.

4.4 Results for cross-parity analysis

For the cross-parity analysis (Table 4.16), including all three parities, parity 3 was only included in certain analyses. Due to limited sow recordings, as well as missing TNB and 70W measurements, parity 3 was not included in TNB and 70W analyses, and only the effects of parity, dam breed x parity, and sire breed x parity were used on this parity. TNB (for parity 1 and 2) was affected ($p < 0.05$) by parity and its interactions with parental breed and season of birth, and 70W (for parity 1 and 2) was affected ($p < 0.05$) only by parity's interaction with sire breed. NBA for all parities was affected by parity, and its interactions with parental breed and season of birth ($p < 0.01$). Birth weight was affected by parity and its interaction with parental breed, 21W by parity and its interaction with dam breed, and 28W by parity ($p < 0.01$). CVB and survival to weaning was affected by parity and its interactions with parental breed ($p < 0.01$).

Table 4.16 Type III Sum of Squares significance for each performance trait per parity-related effect in cross-parity analysis

Variable	Trait							
	TNB	**NBA**	**BiW**	**21W**	**28W**	**70W**	**CVB**	**SURV**
Parity	*	**	**	**	**	0.50	**	**
Dam breed x Parity	**	**	**	**	0.35	0.08	**	**
Sire breed*Parity	*	**	**	0.74	0.99	*	**	**
Season*Parity	**	**	0.8220	0.09	0.09	0.83	0.36	0.10

TNB = total number born, NBA = number born alive, BiW = individual birth weight, 21W = individual 21 day weight, 28W = individual 28 day weight, 70W = individual 70 day weight, CVB = coefficient of variation for birth weight, SURV = survival to weaning

**$p < 0.01$; *$p < 0.05$; actual significance for $p > 0.05$

Litter size only increased significantly between parity 1 and 2 in summer (Addendum E). More detailed tables of the following figures can be found in the addendum. As shown by Figure 4.7, TNB and NBA improved significantly from parity 1 to 3 (3.3% and 11.1%), while within-litter birth weight variation increased (17.8%) ($p < 0.05$). BiW, 21W, and 28W increased ($p < 0.05$) between the first and second parity (10.6%, 15.5%, and 15.3%), but did not increase significantly between the second and third parity, and 21W decreased in parity 3. Survival to weaning is shown in decimal form, where 1.0 is 100% survival to weaning, so as not to make the graph too large. SURV improved from first parity to second (3.4%) ($p < 0.05$), but third parity survival was similar to first parity ($p > 0.05$).

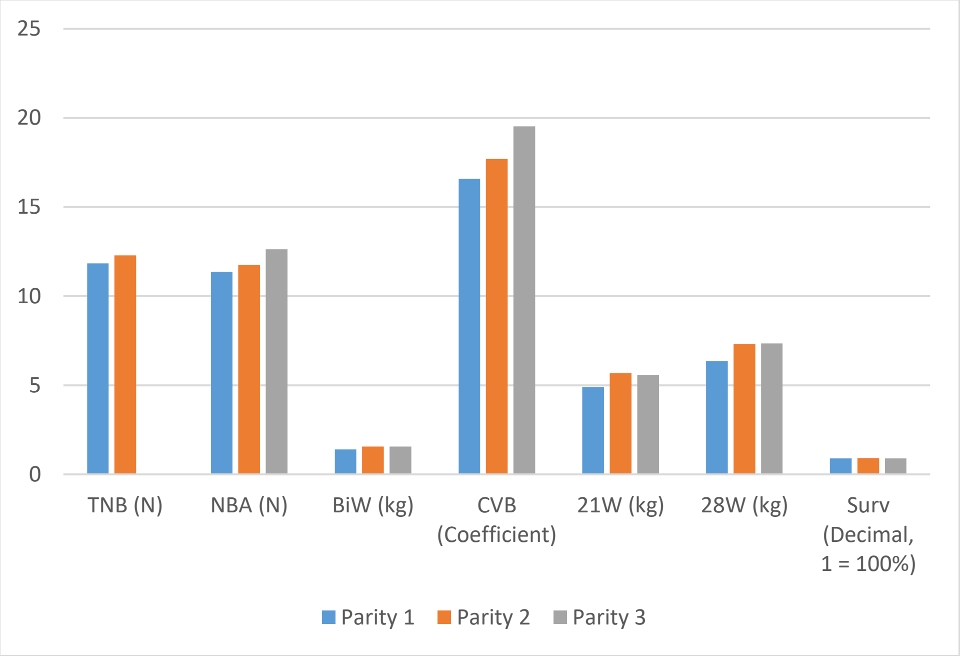

Figure 4.7 Illustration of LS means depicting the influence of parity on performance traits over three parities

Figure 4.8 illustrates the change in performance traits per dam breed over three parities. Litter size didn't change for the Landrace dams, but Durocs showed a 32.5% increase in NBA from parity 1 to 3, and Large White 10% ($p < 0.05$). Landrace dams' piglets birth weights increased by 23.9% over from first to third parity, Large White 9.6% ($p < 0.05$), and Duroc remained constant ($p > 0.05$). Duroc CVB increased by 45.3% from parity 1 to 3, and white breeds only increased by 10-16% ($p < 0.05$). 21W only increased from first to second parity (10-17%) for all breeds ($p < 0.05$). Survival to weaning, shown again as decimals below 1.0, remained constant for Large White litters ($p > 0.05$), while Duroc litters decreased by 10% and Landrace increased by 5.6% ($p < 0.05$).

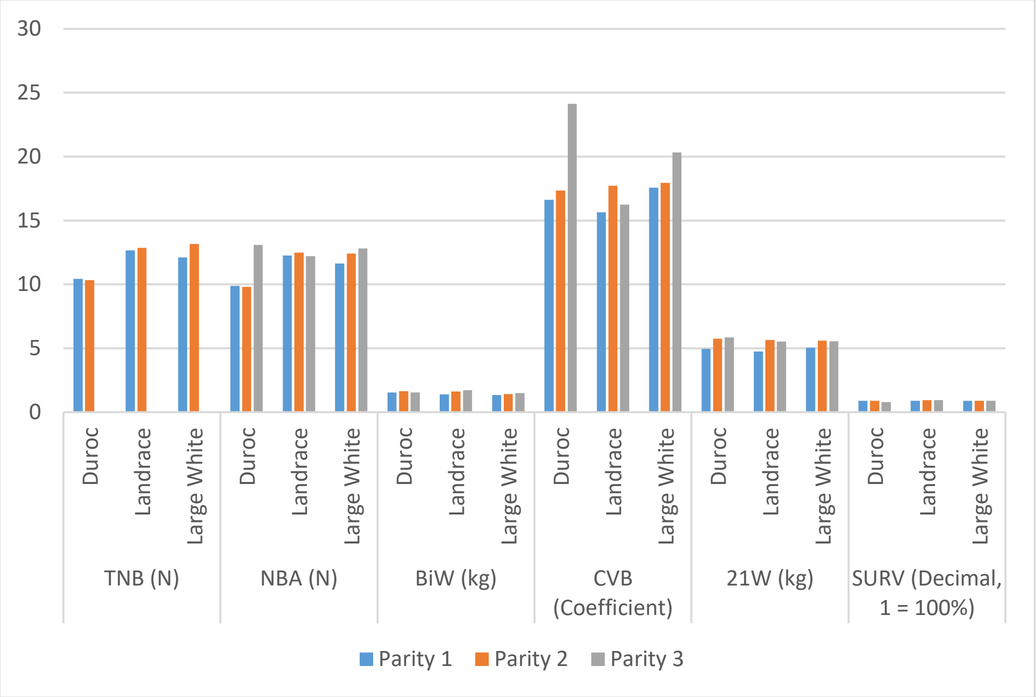

Figure 4.8 Illustration of LS means depicting the influence of parity x dam breed interaction on performance traits across all three parities

Sire breeds (Figure 4.9) shows that NBA increases by 27.7% when Durocs are mated with third parity verses first parity sows, and Landrace sire NBA increases by 12.5% ($p < 0.05$). Duroc sired piglet birth weights remain constant over mated sow parity ($p > 0.05$) but white breeds increase by 19% when mated with third parity sows ($p < 0.05$). CVB of sires increases by 15-24% when mated with higher parity sows ($p < 0.05$). Weight at 70 days is only affected in Landrace sired piglets when mated with second parity sows, showing a decrease of 13.2%, and only Durocs show a fluctuation in survival rate (shown as decimals below 1.0) of piglets, where parity 2 increases by 5.8% but third parity decreases by 11% ($p < 0.05$).

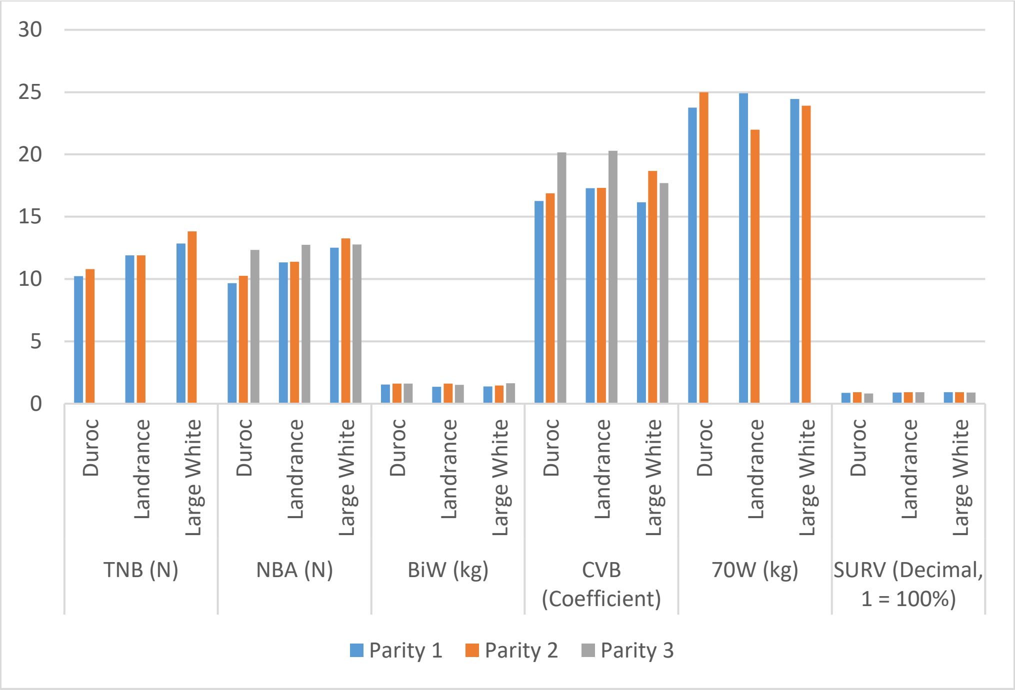

Figure 4.9 Illustration of LS means depicting the influence of parity x sire breed interaction on performance traits across all three parities

The following figures are used to visualize the changes in CVB over parity. The figures show each sow's recorded CVB for each parity, according to their identification (ID) number. Sows missing recordings were those that were removed from the herd during the study. Approximately half of Duroc dams who reached the second parity showed a decrease in CVB from parity 1 to 2, by as much as approximately 2.4-82.5%, and a third showed an increase of approximately 91.2%, (Figure 4.10). Between parity 1 and 3, only one dam decreased (-5.6%), and the rest increased by as much as about 144.5%.

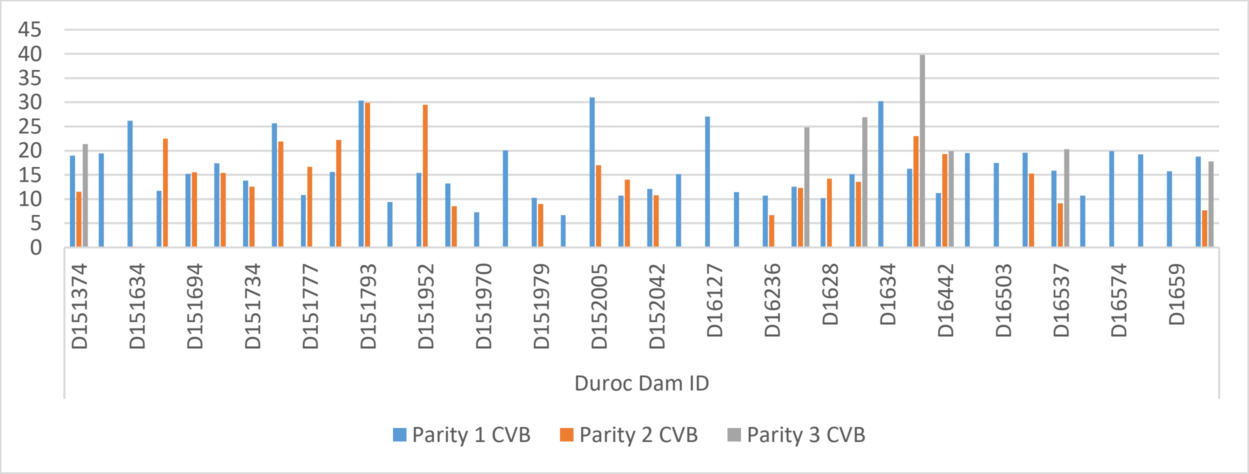

Figure 4.10 Illustration of within-litter birthweight variation over three parities per Duroc dam

Landrace dams showed the opposite of the trend shown by the Duroc dams (Figure 4.11). CVB increased for half of the dams between parity 1 and 2 by as much as approximately 106.7%, and roughly 23-94.7% from first to third parity for two thirds of the dams. Variation decreased for a third of dams by about 2.2-224.1% between the first two parities, and a third of dams decreased from first to third parity by as much as approximately 632%.

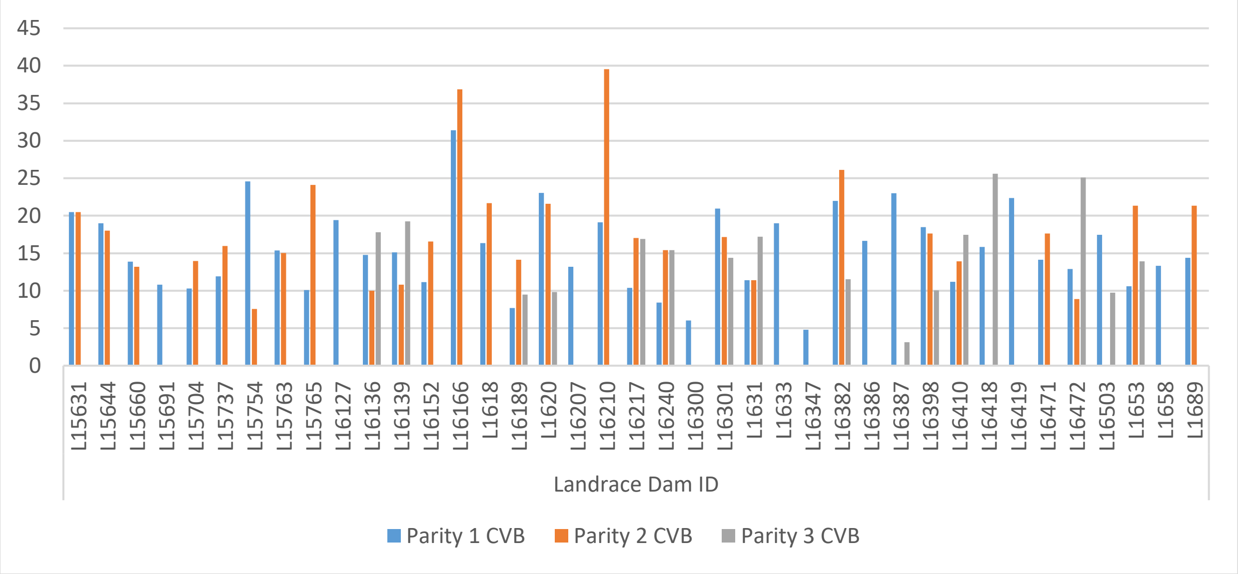

Figure 4.11 Illustration of within-litter birthweight variation over three parities per Landrace dam

Approximately half of Large White dams (Figure 4.12) showed an increase in CVB between the first two parities, as much as about 70.6%, with slightly less showing a decreased CVB, between approximately 0.1-371.4%. The CVB between parity 1 and 3 increased as much as about 95.1% for Large White dam litters, and decreased as much as approximately 37.4% in some cases.

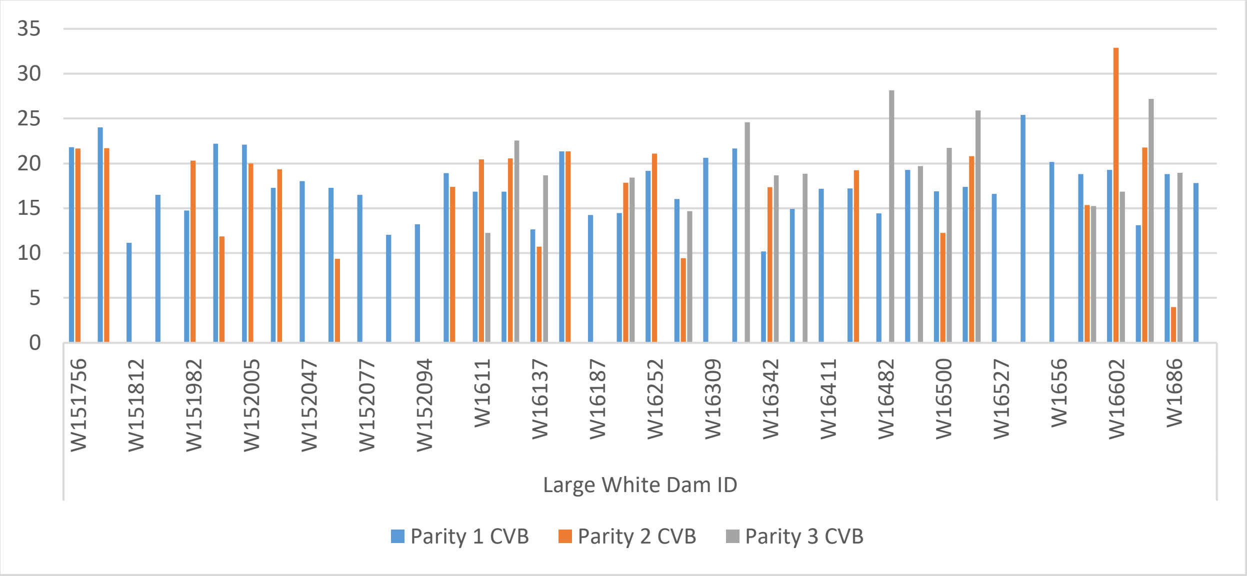

Figure 4.12 Illustration of within-litter birthweight variation over three parities per Large White dam

4.5 Conclusion

In summary, a few trends were observed throughout the study. NBA was affected by sire breed and period of piglet birth in all parities, CVB was affected by dam breed in all parities, and SURV was affected by sire breed in all parities ($p < 0.05$). BiW was affected by sex in the first two parities, and weaning weight was affected by period of piglet birth in the first two parities ($p < 0.05$). When all parities were analysed together, parity itself, and its interaction with dam breed and sire breed, affected NBA, BiW, CVB, and SURV ($p < 0.05$), while 28W was only affected by parity itself ($p < 0.05$). The overall trend of CVB and other traits over parity was an increase with increasing parity. The only Pearson correlation that was at least moderate in nature, across all parities, was that between BiW and 28W (positive), and the first two parities showed a negative correlation between NBA and BiW ($p < 0.05$).

Chapter 5: Discussion

A trait not often recorded in South Africa is piglet birth weight uniformity, which is an important aspect. Low within-litter uniformity of piglets negatively affects performance and welfare factors, as well as management aspects, and warrants further investigation in the South African context. The aim of this study was to investigate the effect that various factors, most notably variation in birth weight within litters, has on piglet performance traits.

Parities will be discussed together, unlike the results chapter. Inconsistencies between performance in this study and expected performance from literature, may in large part be due to limited data rather than actual discoveries of breed or environmental differences. The study was limited in nature, being an on-farm trial, and due to the fact that uniformity was not a routine measurement on the farm.

5.1 Descriptive statistics

For both parity 1 and 2, the Duroc dams had the lowest mean litter size ($p < 0.05$), consistent with breed traits of Durocs, not known for their mothering ability (PBSSA, 2018b). Durocs produced the largest mean litter size in parity 3 ($p < 0.05$), which may be due to the limited data collected for the Duroc breed. The low amount of data was due to recording limitations on-farm. NBA increased for all breeds over the three parities, which was expected as the sows matured (Père & Etienne, 2000; Mesa *et al*., 2015). Dams in this study produced larger litter sizes than that reported in literature (Zindove *et al*., 2013; Tian *et al*., 2016; Kaushik *et al*., 2017; Nuntapaitoon & Tummaruk, 2018).

The mean birth weight for the Duroc, Landrace, and Large White dam breeds over three parities ranged from 1.54 to 1.64 kg, 1.38 to 1.71 kg, and 1.35 to 1.47 kg, respectively. These weights compare well with average piglet birth weight reported in literature for a number of breeds, including maternal lines such as Landrace cross dams (1.46 to 1.56kg) (Huygelen *et al*., 2015; Vallet *et al*., 2016; Nuntapaitoon & Tummaruk, 2018). Higher weights were exhibited by the Durocs in this study (1.54 to 1.64 kg) than Indian Durocs recorded over five parities (1.40 kg) in another study (Kaushik *et al*., 2017). The weights for white breeds (Landrace and Large White) in the current study were similar to most of the literature studied (Freking *et al*., 2016; Huygelen *et al*., 2015; Vallet *et al*., 2016; Vermeulen *et al*., 2016; Kaushik *et al*., 2017), when tested over several parities.

Birth weights are expected to increase with parity, due to a primiparous sow having an underdeveloped uterus. A sow in later parities, thus more mature, will have a larger uterine space with better placental efficiency, and so better able to support the growth of the foetuses (Père & Etienne, 2000; Mesa *et al*., 2015). The birth weights were largest for litters of Duroc dams in the first two parities ($p < 0.05$), which was expected, as the Duroc breed is known to produce good growers (Visser, 2014). Landrace dams exhibited the largest birth weights in parity 3 ($p < 0.05$). The only breed that did not increase in average birth weight in parity 3 was the Duroc, which could partly be due to the low amount of data for the Duroc in parity 3.

Duroc, Landrace, and Large White dam litters produced mean 3 week weights, over the three parities, of 4.95 to 5.85 kg, 4.75 to 5.66 kg, and 5.06 to 5.61 kg, respectively. Breeds were similar ($p > 0.05$) to one another for all three parities. The weights increased with parity, except between parity 2 and 3 for the white breeds, which may be due to decreased data. This weight is an important determinant of mothering ability, as the piglet is almost entirely dependent upon the dam's milk supply up until this stage (Högberg & Rydhmer, 2010), and as such, a decrease in weight in parity 3 may also be due to a build-up of lactation stress on the dam, leading to an insufficient milk supply for piglet growth. Large White and Landrace cross dams in the studies of Zindove *et al*. (2013) and Tian *et al*. (2016) exhibited heavier 21 day weights (5.91 to 5.97 kg) than in the current study, while the synthetic line dams of Zotti *et al*. (2017) were more comparable (5.45 kg).

Piglets from the litters of Duroc, Landrace, and Large White dams over three parities reached weaning weights varying from 6.46 to 7.72 kg, 6.21 to 7.28 kg, and 6.47 to 7.33 kg, respectively. In parity 1, Landrace dams exhibited the lowest weaning weights ($p < 0.05$), while all three breeds produced similar ($p > 0.05$) weights in parity 2 and 3. Weaning weights found in the literature were higher than those in the current study (7.92 to 8.68 kg) over multiple parities (Zindove *et al*., 2013; Freking *et al*., 2016; Kaushik *et al*., 2017).

The 10 week weight for piglets from litters of Duroc, Landrace, and Large White dams for two parities were an average of 24.07 to 26.13 kg, 21.62 to 24.24 kg, and 24.77 to 25.13 kg, respectively. There were no 10 week weights recorded for parity 3, due to on-farm limitations. Landrace dam piglets were heaviest in parity 1, and lightest in parity 2 ($p < 0.05$). Synthetic, Landrace, and Large White cross dams of other studies produced heavier pigs at 70 days (26.6 to 30.1 kg), over multiple parities, than the current study (Douglas *et al*., 2014; Craig *et al*., 2017b). Sires are not specified in this section, but it would be expected that piglets with a Duroc sire would reach the heaviest weights at 10 weeks. It is the point at which animals that were not selected for breeding were marketed for slaughter, and Durocs are known as preferred terminal sires due to their ability for growth (Whittemore & Kyriazakis, 2006; Rothschild & Ruvinsky, 2011).

Uniformity of birth weight within litters was measured using coefficient of variation, the highest coefficient indicating the least uniform. The within-litter coefficient of variation of birth weight in Duroc, Landrace, and Large White dam litters over three parities varied from 16.66 to 24.13, 15.65 to 24.13, and 17.56 to 20.32, respectively. The coefficient of variation in this study is comparable to the overall average found in the SA Landrace x Large White dams of Zindove *et al*. (2013), at 17.44, and the average of 21% observed by Quesnel *et al*. (2008) over 7+ parities. The variability of birth weight in a Zimbabwean Landrace x Large White herd ranged from 0-87.5% over several parities (Marandu *et al*., 2015), which appears more varied than this study. Landrace dam litters exhibited the lowest CVB in the first and third parity ($p < 0.05$), and Large White the highest in the first parity and Duroc highest in the third parity ($p < 0.05$). All breeds were similar in the second parity ($p > 0.05$). CVB appeared to increase with increasing parity, most notably for the Duroc dams.

Uniformity could have decreased due to the sow's body condition loss during lactation, especially as primiparous sows must mobilise body reserves in order to continue their own growth as well as support their litter (Bierhals *et al*., 2012). Inadequate recovery before conception leads to insufficient restoration of follicular development, which affects the embryo quality and ability to develop. This leads to variation in fetal development (Rutherford *et al*., 2013; Wientjes *et al*., 2013b), and the lack of sow recovery may have compounded with each parity. Alternatively, or additionally, variation coefficients could have been affected by decreasing amount of data per parity. However, sows are expected to produce more uniform litters as they mature. More mature sows will have a larger uterine area for foetal growth, as well as a better placental efficiency (Père & Etienne, 2000; Mesa *et al*., 2015), which should decrease the in utero competitive factor which leads to variation. Hence, various management practices should be employed in order to decrease the effect of body condition loss and make use, instead, of the capabilities of the more mature sows. Fostering out should be correctly employed between 24 and 48 hours postpartum, to decrease stress on the sow's lactation ability and increase uniformity of the litter to decrease competition between piglets (Heim *et al*., 2012; Muns *et al*., 2014). Optimal nutritional support for the sow may also be employed to decrease condition loss, via insulin-stimulating diets fed to sows prior to mating (Weintjies *et al*., 2012), or supplementing gestating sows with arginine and glutamine (Van Barneveld & Hewitt, 2016), both shown to increase litter uniformity.

Average survival to weaning for litters of Duroc, Landrace, and Large White dams over three parities were 80-95%. The highest survival rate ($p < 0.05$) was exhibited by Landrace dam litters for parity 2 and 3, while survival rate was similar ($p > 0.05$) for all breeds in the first parity. Survival rate would be expected to increase with parity, as mothering experience of the dams increased. This was not seen throughout, possibly as a result of lactation body condition loss. The survival to weaning of piglets in this study were higher compared to those reported by Freking *et al*. (2016) (USA) in all three parities. The Indian Duroc preweaning mortality rate found by Kaushik *et al*. (2017) was 15.61% over five parities, which was comparable to the Durocs of this study. Zotti *et al*. (2017) reported a mortality of 11.1% which is also comparable to the current study. SA Landrace x Large White dams produced piglets that had an average survival to weaning of 87.63% (Zindove *et al*., 2013), indicating a lower survivability overall than this study.

5.2 Environmental effects affecting performance traits

Performance traits were compared according to the environmental effects, specifically season and year of piglet birth, and the farrowing and weaning room in which they were housed. Both the environmental and animal effects did not affect traits consistently through parities, as was seen in Table 4.1, 4.6, and 4.12.

Period (season and year) of birth was found to affect various performance traits in this study, but not for all parities. In parity 1, NBA was largest ($p < 0.05$) in autumn of 2017, but was similar to summer 2016 ($p > 0.05$), parity 2 had the highest ($p < 0.05$) TNB and NBA in summer 2017, and parity 3 had the highest ($p < 0.05$) NBA in spring. If it is assumed that conception took place approximately one season prior, the summer of parity 1 had a low probability of heat stress, or the cooling procedures prevented heat stress. It has been documented that heat stress affects fertilization rate, in-utero survival rates, and fetal development (Boddicker *et al*., 2014; Swinbourne *et al*., 2014; Johnson *et al*., 2015). Parity 1 results are contrary to Wegner *et al*. (2014), who found that sows inseminated in summer and autumn produced smaller litter sizes. Knecht & Duziński (2014) and Wegner *et al*. (2016) also found that the lowest NBA was observed when insemination occurred in the warmer months. Hagan & Etim (2018) observed an increase in litter size in the wet seasons, which were cooler. This is contrary to the observations of Quesnel *et al*. (2008), who found that season of conception had no effect on uniformity at birth. Period of piglet birth was not found to affect ($p > 0.05$) TNB in parity 1.

Birth weight was highest ($p < 0.05$) in parity 3 in spring, presumably conceived in winter. This finding differs with the reports of Quesnel *et al*. (2008), where the largest birth weights were observed when piglets were conceived in spring. Kaushik *et al*. (2017) found that year, but not season, affected birth weights. Period of birth did not affect ($p > 0.05$) birth weight in the first two parities. Uniformity of birth weight within the second parity litter was highest ($p < 0.05$) in spring, in the current study, therefore being a winter conception. This supports the theory of heat stress affecting in utero development (Dhakal *et al*., 2013; Boddicker *et al*., 2014), and some piglets being more affected than others, due to placental vascularity differences in utero (Rutherford *et al*., 2013) possibly causing weight variation. Uniformity was not affected by period of birth in parity 1.

Second parity piglets' 3 week weight was higher ($p < 0.05$) in spring and summer births than autumn and winter in parity 2, which could be due to lack of cold stress, as piglets would otherwise have a higher energy expenditure for thermoregulation (Marandu *et al*., 2015). Weight at 3 weeks was not affected ($p > 0.05$) by season in any other parity. Weaning weight in parity 1 was lowest ($p < 0.05$) in summer 2017 births, and parity 2 weaning weight was higher ($p < 0.05$) in spring and summer 2017 births, and parity 3 was unaffected ($p > 0.05$). This difference may be due to either less data with increasing parity, or that the piglets from a more mature sow were better able to cope with warmer seasons, having had a better *in utero* environment. Marandu *et al*. (2015) found that the lowest weaning weights occurred in autumn, over a range of ten parities, and Hagan & Etim (2018) observed larger weaning weights from wet, cooler season births. Knecht *et al*. (2015) partly attributed their finding of lower weaning weights in summer to the effects of heat stress on the dam and her lactation efficiency.

The 10 week weights in parity 1 were lowest ($p < 0.05$) from spring 2016 births, hence they were possibly exposed to heat stress during growth in summer. Season was not significant ($p > 0.05$) in parity 2 for 70W. Survival to weaning was only affected ($p < 0.05$) by period of birth in parity 3, where mortality decreased from spring to autumn births. This is contrary to the studies of Kaushik *et al*. (2017), where mortality was highest in summer, and Marandu *et al*. (2015), where mortality was highest in autumn. Similar results were reported by Wegner *et al*. (2014), where mortality was lowest in spring, as both spring and autumn can be seen as mild seasons. Hagan & Etim (2018) found that although litter size and piglet weights were higher from wet season births, mortality was also higher, due to lower temperatures. Colder months require a higher energy expenditure, and disease incidence may play a role in poor performance (Marandu *et al*., 2015).

The effect of farrowing house on birth weight and its uniformity was deemed to be coincidental, as they would have been housed in a different facility for most of their gestation. A management effect was seen in the form of differences in performance in rooms, which were presumed to have been under the same environmental influences. There may have been differing levels of management in these rooms, leading to differences in cleanliness and animal assistance. Both 3 week weight and weaning weight were highest ($p < 0.05$) in room D, and lowest ($p < 0.05$) in room B, in parity 1. It was not significant ($p > 0.05$) in parity 2. This could be seen as a stockman effect. The 10 week weight was also affected by the room of the weaner house in which they were kept, in parity 1 but not parity 2, and this must also be a stockman effect, as all weaner rooms are assumed to share the same conditions. The lack of significant difference in parity 2 may be due to the maturation of the dam. Survival rate to weaning in parity 2 was lower ($p < 0.05$) in rooms A and E, which could be due to the draft from the outside, as staff entered and exited the house. No literature was found that refers to rooms within a house as an effect, possibly because it is largely deemed negligible. As has been stated here, it is assumed to be largely an attribute of management rather than environment itself. It may simply be suggested that doors be kept more diligently closed in the farrowing house to avoid drafts, and management of a similar standard be maintained throughout the house.

5.3 Animal effects affecting performance traits

Animal effects, which included dam breed, sire breed, dam parity, and piglet sex, were tested for significant effect upon performance traits of the piglets. The effect on the piglet of being fostered out could either be due to the ability of the natural or foster dam to nurse, or due to litter environment factors such as competition amongst piglets. In this study, foster status was included as an animal effect.

Parity was used as an entirely separate, but important, effect, as primparous sows are documented to have a poorer mothering ability compared to multiparous sows (Bierhals *et al*., 2012; Zindove *et al*., 2013; Mesa *et al*., 2015; Craig *et al*., 2017b). They are smaller in size and weight, and therefore have less uterine space for foetal growth and a lower ovulation rate (Wegner *et al*., 2014; Mesa *et al*., 2015; Craig *et al*., 2017b). Additionally, they are required to adapt to various physiological and behavioural changes involving farrowing and lactation, along with their own continued growth, which diverts less nutrients into milk production (Zindove *et al*., 2013). TNB and NBA increased ($p < 0.05$) with parity in this study, as is expected with the increase in uterine length and ovulation rate of the sow, and supports the findings of Tian *et al*. (2016) and Wegner *et al*. (2014). Hagan & Etim (2018) also found an increase with parity, although first and second parity were quite similar, and average litter size at farrow decreased again at parity 5.

Within-litter birth weight variation increased ($p < 0.05$) up to the third parity, which agrees with the findings of (Zotti *et al*., 2017), where parity had a positive linear effect on CVB. Tian *et al*. (2016) also found that CVB increased from the second to the third parity, and Quesnel *et al*. (2008) observed less heterogenous litters in first and second parity sows than in older sows. Birth weight, 3 week weight, and weaning weight increased ($p < 0.05$) from the first to second parity, but the second and third parity remained similar ($p > 0.05$). The similarity may have been due to limited data in both parities, but the increase from parity 1 to 2 agrees with the findings of Tian *et al*. (2016) and Hagan & Etim (2018). Craig *et al*. (2017a, 2017b) also found that multiparous sows produced piglets that were heavier at all stages than piglets of primiparous sows. Survival to weaning increased ($p < 0.05$) from the first to the second parity, which was likely due to the dam's increasing maturity, but decreased ($p < 0.05$) again in the third, in this study. This may have been due to a lack of lactation recovery, building from the first parity, or as a result of insufficient data. This is in line with the study of Hagan & Etim (2018), who observed an increase in survival in parity 2, but a decrease thereafter. Nuntapaitoon & Tummaruk (2018) showed only a minor increase in survival to weaning with increasing parity. Wegner *et al*. (2014), however, found the highest number of weaned piglets in primparous sows, and Zotti *et al*. (2017) found no significant parity effect. Weight at 10 weeks was not affected ($p > 0.05$) by parity, possibly because this trait may not be affected by maternal genetics, but only by piglet genetics.

Sex of the piglet was found to affect ($p < 0.05$) its birth weight in parity 1 and 2, but not parity 3 ($p > 0.05$), as well as only second parity 3 week weight ($p < 0.05$), with boars consistently being larger. This finding is in agreement with Marandu *et al*. (2015), who found that males had a higher average daily gain and were larger at weaning, and Milligan *et al*., (2001) and Dunshea *et al*. (2003) found that males were heavier at birth, but sex did not affect pre-weaning gain. Palencia *et al*. (2017) also reported that males were larger than females during various periods of gestation, presumably due to testosterone effects, which would carry through to birth weight.

First parity NBA was largest ($p < 0.05$) in the Landrace dam litters, and uniformity was also highest in these litters, consistent with the Landrace's mothering ability (Visser, 2014), and NBA in parity 2 was lowest in the Duroc dam litters, as expected (PBSSA, 2018b). Hagan & Etim (2018) found that litter size was larger in Large White x Duroc cross dams than in Large White dams. The breed of the piglet's dam affected CVB in both parity 1 and 2, such that all dams produced significantly different ($p < 0.05$) CVB values. Duroc dams did not produce the litters with the highest birth weight variation in parity 1, and CVB was lowest ($p < 0.05$) in second parity Duroc dam litters, contrary to expectations, as uniformity would be assumed to be a factor of mothering ability. Birth weight in parity 1 was not affected by dam breed ($p > 0.05$), but parity 2 was most different between Large White and Duroc dams, Durocs having heavier ($p < 0.05$) piglets, consistent with breed expectations. Large White x Duroc cross dams, however, produced heavier piglets than purebred Large White dams, in the study of Hagan & Etim (2018). Survival rate was higher ($p < 0.05$) in the Landrace dams' second parity litters, and Duroc dam litters were lowest ($p < 0.05$) in parity 3, both consistent with their mothering ability. Parity 1 was not affected by dam breed ($p > 0.05$). Hagan & Etim (2018) observed a significantly lower survival rate in Large White litters compared to litters of Large White x Duroc crosses. The 10 week weights were different ($p < 0.05$) across all dam breeds, Duroc again producing the largest piglets, as this breed is expected to do. Parity did not affect ($p > 0.05$) 70W in this study, although Craig *et al*. (2017b) observed that first parity piglets were significantly smaller than multiparous sows' piglets.

The sire breed of the litters from parity 1 and 2 sows affected litter size, such that Duroc sires produced the smallest ($p < 0.05$) litters and Large White the largest ($p < 0.05$), which was in line with the mothering ability of the breeds (Rothschild & Ruvinsky, 2011; PBSSA, 2018b). NBA was not affected ($p > 0.05$) by sire breed when mated to third parity sows. Birth weight was also heaviest ($p < 0.05$) for parity 1 (dam) piglets from Duroc sires, as was expected, as they are known for growing ability (Visser, 2014), but it did not affect BiW when mated with parity 2 or 3 sows. It was found, by Vermeulen *et al*. (2016), that sire line affected birth weight, mainly by affecting gestation length. Longer gestation lengths produced larger piglets, and shorter gestation lengths were experienced by faster growing piglets, that then experienced compromised growth thereafter. Duroc and Landrace sires produced litters of similar ($p > 0.05$) within-litter birth weight variation, lower ($p < 0.05$) than Large White sires, when mated with parity 1 and 3 sows. Duroc sires would have been expected to produce higher variation, but their growing ability may have improved uniformity. CVB was not affected by sire breed when mated to parity 2 sows ($p > 0.05$). Landrace sires produced the heaviest ($p < 0.05$) pigs at 10 weeks when mated to gilts, where it would have been expected that Durocs would have been heaviest, which occurred in parity 2 matings ($p < 0.05$), as they are known as good growers and terminal sires (Visser, 2014). Litters of Large White sires had the highest ($p < 0.05$)

survival rate to weaning when mated with gilts, and Landrace sired litters with the highest ($p < 0.05$) survival in parity 2 matings, both breeds known for mothering ability and piglet survivability (Rothschild & Ruvinsky, 2011; Visser, 2014). Duroc sires produced the lowest ($p < 0.5$) survival when mated to parity 3 sows. In another study, by Huang *et al*. (2003), sire breed of the dam itself was investigated rather than sire of the piglets, as it was deemed a more important effect for reproductive performance. NBA was higher when the sire of the dam was a Landrace, and survival to weaning was higher in litters where the dam's sire was a Duroc.

Considering the interaction of dam and sire breeds on piglet performance, the Landrace and Large White breeds produced larger ($p < 0.05$) litters, and Duroc involvement produced smaller ($p < 0.05$) litters. Both outcomes would be anticipated, due to breed expectations (Rothschild & Ruvinsky, 2011; Visser, 2014; PBSSA, 2018b). The study of Hagan & Etim (2018), however, observed larger litter sizes in Duroc cross lines. Contrary to expectation, a first parity Duroc dam bred with a Duroc sire produced the lowest variation ($p < 0.05$) within the birth weights of the litter. This may be due to the growing ability of the breed, allowing the smaller piglets to compensate for a possibly poorer environment in utero. Second parity Large White dams appeared to produce the lower ($p < 0.05$) birth weights with any mating, while second parity Landrace dams bred with Duroc sires produced the heaviest ($p < 0.05$) piglets at birth, due possibly to complementarity of parental traits. Hagan & Etim (2018) found that purebred Large White piglets had larger birth weights than Large White Duroc crosses. Landrace x Duroc pairings in the current study also produced the lowest variation (while being significantly different from other values, $p < 0.05$) in birth weights within the second parity litters. Duroc dams bred with Landrace sires in the second parity had the lowest ($p < 0.05$) survival rate to weaning in their litters, but when bred with Large White sires, they had the highest ($p < 0.05$) piglet survival rate. The complementarity between Duroc and Large White may therefore be more favourable from this standpoint. The purebred Duroc piglets had the lightest ($p < 0.05$) weight at 10 weeks, and this may be due to the poor mothering ability of the dam up to weaning (PBSSA, 2018b). The litters from first parity Large White dams and Landrace sires had the heaviest ($p < 0.05$) weight at 10 weeks, which may be a result of the mothering ability of both breeds (Rothschild & Ruvinsky, 2011; Visser, 2014), allowing good growth in the piglets' early life.

It was expected that piglets would perform better when left with their natural dam, as was found by Marandu *et al*. (2015), where cross fostering significantly reduced weaning weight and number weaned. This was attributed to the either the piglets' failure to adjust, or the piglet being taken from a poor mother, which would have a permanent effect. Piglets not kept on their natural dam in parity 1, did have a lower ($p < 0.05$) survival to weaning than those kept with their natural dam. However, in this study, the weight at 3 weeks in parity 1 was heavier ($p < 0.05$) for piglets that were fostered out, and this may be because they were moved to more productive sows and smaller litters, allowing better growth than on their natural dam. This may have been either by chance or by design, although stockmen were requested to foster piglets at random. Milligan *et al*. (2001) reported, however, that fostering did not affect weights beyond three days old. Fostering status did not affect any other traits in any parity ($p > 0.05$).

5.4 Correlations between performance traits

Pearson correlations were estimated for a series of comparisons, and only significant correlations ($p < 0.05$) are reported here. Most of these correlations were moderate to low, similar to studies such as that of Wolf *et al.* (2008). As was expected, birth weight was (moderately) positively, and favourably, correlated with 3 week weight, weaning weight, in both parities, and with 10 week weight in parity 1. This means that a small piglet will remain small, supporting the claim that piglets rarely experience compensatory growth (Václavková *et al*., 2012; Magnabosco *et al*., 2015). This was also found by Ilatsia *et al*. (2008), Freking *et al*. (2016), Vermeulen *et al*. (2016), Zotti *et al*. (2017), where piglets that were light at birth were slow growers, and remained lighter at weaning, through to slaughter, due to the smaller secondary muscle fibres and impaired intestinal development of undersized piglets. Zindove *et al*. (2013) stated that birth weight was genetically correlated to future performance of a piglet, due to the expectation that heavier piglets would more efficiently stimulate teats, and found that mean birth weight was correlated to mean 3 week weight. Weight at 3 weeks, in the current study, was highly correlated with weaning weight in both parity 1 and 2, which would be expected as the two weights are measured only a week apart. Milligan *et al*. (2001) observed that 3 week weight was affected by litter size at birth, where smaller litters had a higher weight gain. First and second parity 3 week weight and weaning weight was also moderately correlated with 10 week weight, the point at which pigs undergo performance testing. Ilatsia *et al*. (2008) found a high correlation of birth weight and 3 week weight with weight at 8 and 12 weeks. Thus, it is not financially advisable to raise light pigs at birth, to slaughter.

Birth weight in both parity 1 and 2 was (weakly) negatively and unfavourably, correlated with litter size, such that larger litters were likely to have lighter piglets. This is extremely unfavourable, as both larger piglets and larger litter sizes are important for a profitable farm. However, the correlation is low, so it may not be that problematic in practice. Tian *et al*. (2016) and Quesnel *et al*. (2008) also found a decrease in piglet birth weight with larger litter size, and other literature agrees that larger litter sizes lead to smaller birth weights (Václavková *et al*., 2012; Zindove *et al*., 2013; Magnabosco *et al*., 2015). Zindove *et al*. (2013) also found that NBA was negatively correlated to mean weight at 3 weeks and weaning. Litter size in parity 2, in the current study, was only weakly correlated with 3 week and weaning weight, which may mean that as the parity of the dam increases, the piglets are better equipped to compensate for small birth weight due to the sows improved mothering ability.

No meaningful correlations were observed in this study for survival to weaning. Literature states that larger litter sizes, and lighter piglets, should experience a higher preweaning mortality rate, due to poor mothering ability associated with sows producing larger litters (Quesnel *et al*., 2008; Václavková *et al*., 2012; Zindove *et al*., 2013; Magnabosco *et al*., 2015). Nuntapaitoon & Tummaruk (2018) found a significant correlation between preweaning mortality and litter size (positive), as well as with birth weight (negative). They propose that a larger litter size, particularly over 16 piglets, leads to a prolonged farrowing time, which negatively impacts the sows health and lactation ability, as well as the piglets vitality and ability to grow. Lighter piglets are also less able to maintain their body temperature, and are thus susceptible to hypothermia, and are less able to compete for milk consumption, and therefore have a lower passive immunity (Tian *et al*., 2016). Slightly conversely, Marandu *et al*. (2015) found that very small litter sizes had the highest risk of piglet mortality, and moderate litter sizes had the highest survival rate.

The focus of this dissertation was on whether birth weight uniformity may be used as a predictor of the future performance of the piglets within a litter. It was, however, found that uniformity did not strongly correlate with any of the analysed performance traits. This may be due to the small size of the study, and the decreasing amount of data with parity. Only in the third parity did CVB correlate moderately, and negatively (-0.34), with birth weight. This result adds to the accepted literature, in that higher variation in the birth weights of a litter leads to a higher proportion of lightweight piglets (Quesnel *et al*., 2008; Václavková *et al*., 2012; Alvarenga *et al*., 2013; Magnabosco *et al*., 2015, 2016; Yuan *et al*., 2015). The average correlation over three parities found between CVB and birth weight, in this study, was -0.21, suggesting a weak correlation. The correlation between CVB and weaning weight was even lower than this, thus no significant link was shown between uniformity at birth and future growth performance. However, if it is considered that birth weight is moderately and favourably correlated with future weights, by using the concept of the transitive property, because of the correlation between CVB and birth weight, CVB can be considered a predictor of future growth performance.

Tian *et al*. (2016), Wolf *et al.* (2008), and Milligan *et al*. (2002) found an increase in CVB with increasing litter size, due possibly to uterine crowding restricting the growth of some piglets in utero. As can be found in the addendum, the correlation of birth weight with CVB, over three parities, is an average of 0.19, increasing with increasing parity. The increase in CVB with parity was expected, due to the effects of the sow's body condition loss during lactation on uniformity, as discussed in descriptive statistics. A correlation between CVB and survival to weaning was not found in parity 1 of this study, but a moderate and negative correlation (-0.22) was found in parity 2 and 3. Thus, in multiparous sows, it can be seen that a higher within-litter birth weight uniformity leads to a lower mortality rate before weaning. Marandu *et al*. (2015) also found that preweaning mortality increased with higher within-litter birth weight variation, as higher variation means more lightweight piglets, who are less able to compete for milk consumption (Marandu *et al*., 2015), and who have a reduced intestinal development, affecting their vitality (Zotti *et al*., 2017). A similar correlation value was found by Wolf *et al.* (2008) between CVB and survival to weaning, and Milligan *et al*. (2002) also found that survival was highest in less variable litters. Fix *et al*. (2010) found no effect of CVB on survival to weaning.

5.5 Conclusion

Significant conclusions cannot be drawn from these results, due to the limited size of the data set. Although the results of this study did not always agree with similar studies, trends in descriptive statistics generally corresponded with previously published literature. These results largely agreed with breed standards and parity expectations. The effects and correlations may have been more difficult to find trends in due to the lack of data, and limited trends were found to carry through parities. However, there were no observations within environmental or animal effects that were outside the realm of possibility according to the literature. The correlations were very low for associations that should exist as is stated within the literature.

Chapter 6: Conclusion and recommendations

This study was requested by SAPPO, and aimed to investigate whether birth weight uniformity had merit enough to be included in the breeding objectives of the South African pig breeders. This was extended to other litter traits such as litter size, piglet weights, and piglet survival. These traits were observed over three parities in three breeds, the Duroc, Landrace, and Large White, on a working stud farm. In order to conclude what factors might affect these traits, GLM procedures were run, which included dam breed, sire breed, the interaction between dam and sire breed, piglet sex, period of piglet birth, room of piglet birth, and piglet room after weaning. The traits were then analysed to obtain Pearson correlations, to investigate potential associations.

The descriptive statistics were found to follow the trend of breed and parity expectations, to a large extent. The effects were quite varied, but the dam breed was found to be a significant effect ($p < 0.05$) on CVB in every parity, similarly between NBA and sire breed and period of piglet birth, and SURV and sire breed ($p < 0.05$). Parity, and its interaction with both dam breed and sire breed, affected CVB, NBA, BiW, and SURV significantly ($p < 0.05$), but 28W was only affected by parity, and 21W only by parity, and its interaction with dam breed ($p < 0.05$). These effects largely behaved as they should. NBA and SURV was lower for Durocs, not known for their mothering ability, but CVB was only highest in the Duroc in the third parity, suggesting that the growth ability of the Duroc may contribute to a decreased CVB.

Seasonal effect on NBA was less straightforward and varied with parity, possibly due to variation in intensity of season, or effect of parity, or lack of data. NBA, BiW, and SURV mostly increased with parity, as was to expected due to increase in dam maturity. CVB decreased, presumably due to the increase in litter size and the lack of recovery between lactations, as literature had predicted. Pearson correlation coefficients were mostly moderate to low in this study, despite the expectation that traits such as CVB and litter size, and CVB and weights, should be significantly unfavourably correlated. The only correlation that carried through parities was that between birth weight and weaning weight ($p < 0.05$), which leads to the conclusion that low birth weight piglets will remain lighter in weight, which agrees with literature.

CVB was found to be significantly affected ($p < 0.05$) by dam breed, hence this would be the best method with which to influence CVB. However, since no significant correlation was drawn between CVB and any other traits, it cannot be determined whether CVB would be a beneficial litter trait to include in the breeding objective of the South African pig industry, although literature suggests that it would be. Thus, no significant conclusion can be drawn from this study regarding within-litter birth weight uniformity, and it requires further investigation.

Recommendations

From this study, it may be recommended that including individual piglet measurements may be beneficial to better understand the growth and reproductive ability of the piglets in the future. It will require a dedicated study with a sufficient number of sows, that will have both cost and labour implications. A dedicated study will require a trial on an experimental farm, where sows need not be culled during the trial. Furthermore, fostering should either be prevented or controlled. More animals should also be included for a larger sample size, and animals should be followed up to a higher parity.

Literature indicated that studies followed pigs up to parity 5, on average. This allows time for sows to adjust properly to the breeding system over time to show their true performance ability, allowing more accurate results. Originally, this study was also to include the performance of the piglets from the first parity of the studied sows. This would allow the trial to observe whether gilts born to more uniform litters, in turn, produced more uniform litters, and whether their reproductive ability was of a better standard, according to litter traits recorded. This would be a useful observation and should be included in future trials.

In conclusion, it should be noted that is the first trial of its kind in South Africa to study piglet birth weight uniformity. The study confirms that there is merit for further investigation, and it holds potential for contributing to the improvement of overall production.

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Addendum A: Materials and Methods

<table>
<tr><td colspan="4">Dam number: __________
Parity</td><td colspan="4"></td></tr>
<tr><td colspan="4">Date of farrow</td><td colspan="4"></td></tr>
<tr><td colspan="4">Pen number</td><td colspan="4"></td></tr>
<tr><td colspan="4">Natural/induced farrow</td><td colspan="4"></td></tr>
<tr><td colspan="2">Total number born</td><td colspan="2"></td><td colspan="2">Number born alive</td><td colspan="2"></td></tr>
<tr><td colspan="3">Date:</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Piglet no.</td><td>CF dam</td><td>G/B</td><td>BiW</td><td>21W</td><td>28W</td><td>70W</td><td>Weaner house</td></tr>
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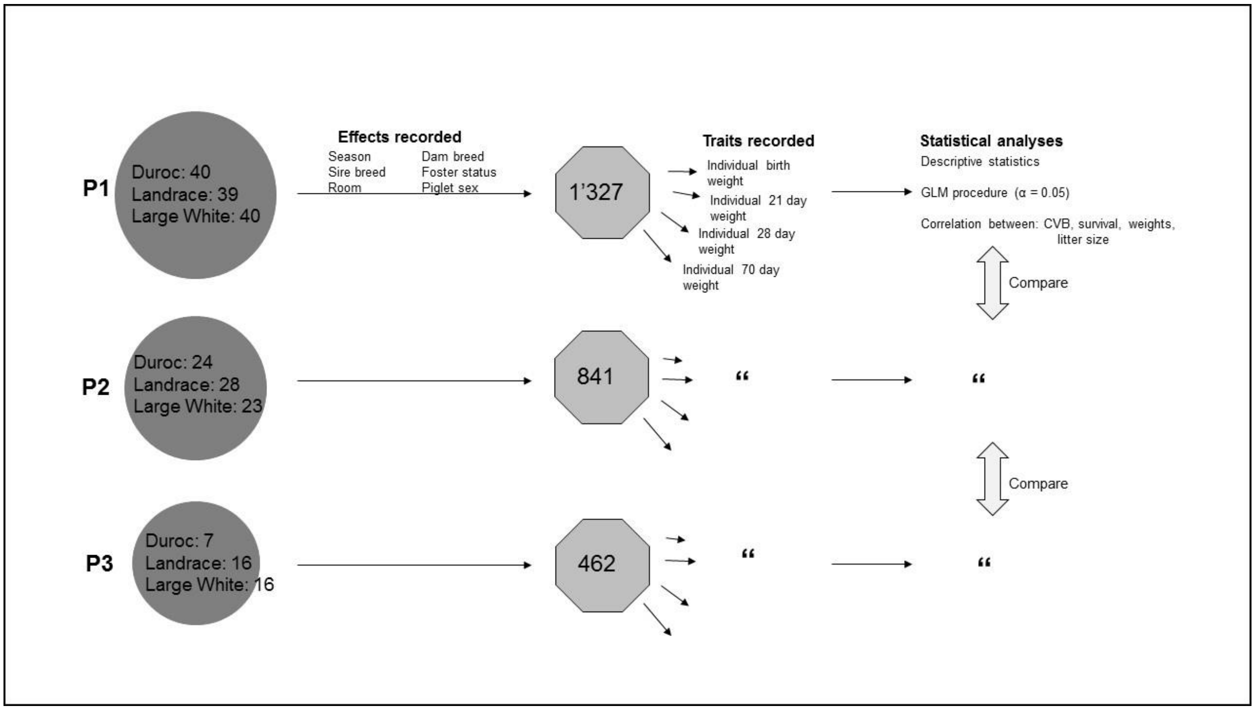
</table>

CF = cross-foster dam, G/B = gilt or boar, BiW = individual birth weight, 21W = individual 21 day weight, 28W = individual 28 day weight, 70W = individual 70 day weight

Figure A.1 Data collection sheet template



P = parity, GLM = general linear model, CVB = within-litter birth weight variation

Figure A.2 A diagram to illustrate the methodology of the study

Addendum B: Parity 1

Table B.1 LS means ±SE depicting the influence of piglet sex on performance traits for parity 1

Trait	Sex	
	Boar	Gilt
BiW (kg)	1.43±0.01^{a}	1.39±0.01^{b}

BiW = individual birth weight

$^{a, b, c}$ – Denote significant differences between means within fixed effects in rows (p <0.05)

Table B.2 LS means ±SE depicting the influence of farrowing room on performance traits for parity 1

Trait	Farrowing Room				
	A	B	C	D	E
21W (kg)	4.90±0.07	4.72±0.07^{b}	4.92±0.07	5.06±0.08^{a}	4.79±0.07
28W (kg)	6.36±0.04^{cd}	6.09±0.04^{b}	6.43±0.04^{ac}	6.59±0.05^{a}	6.19±0.05^{bd}

21W = individual 21 day weight, 28W = individual 28 day weight

$^{a, b, c, d}$ – Denote significant differences between means within fixed effects in rows (p <0.05)

Table B.3 LS means ±SE depicting the influence of weaning room on performance traits for parity 1

Trait	Weaning Room				
	A	B	C	D	E
70W (kg)	24.21±0.30^{b}	24.07±0.31^{bc}	26.08±0.33^{a}	24.87±0.35^{ab}	22.67±0.38^{c}

70W = individual 70 day weight

$^{a, b, c}$ – Denote significant differences between means within fixed effects in rows (p <0.05)

Table B.4 LS means ±SE depicting the influence of foster status on performance traits for parity 1

Trait	Natural	Unnatural
21W (kg)	4.86±0.03^{a}	5.05±0.13^{b}
SURV (%)	0.89±0.00^{a}	0.88±0.01^{b}

21W = individual 21 day weight, SURV = survival to weaning

$^{a, b, c}$ – Denote significant differences between means within fixed effects in rows (p <0.05)

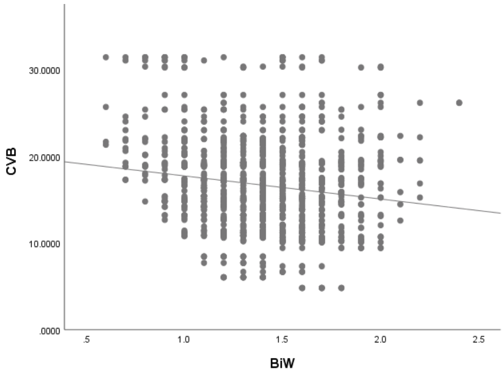


Figure B.1 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between within-litter birth weight variation (CVB) and individual birth weight (BiW) for parity 1 ($R^2 = 0.024$)

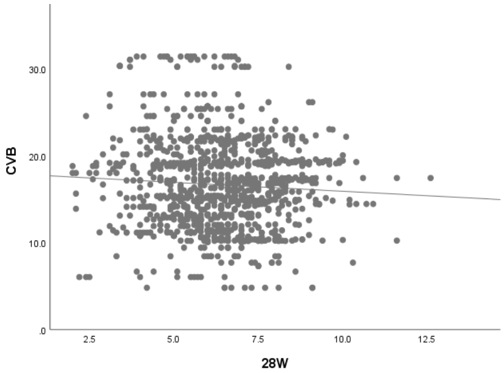


Figure B.2 Scatter plot illustrating the Pearson correlation ($p < 0.05$) between within-litter birth weight variation (CVB) and individual weaning weight (28W) for parity 1 ($R^2 = 0.004$)

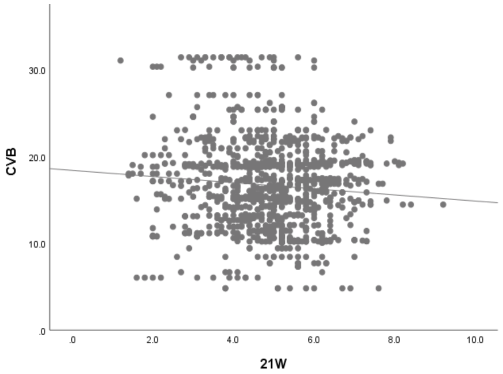


Figure B.3 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between within-litter birth weight variation (CVB) and individual 21 day weight(21W) for parity 1 ($R^2 = 0.007$)

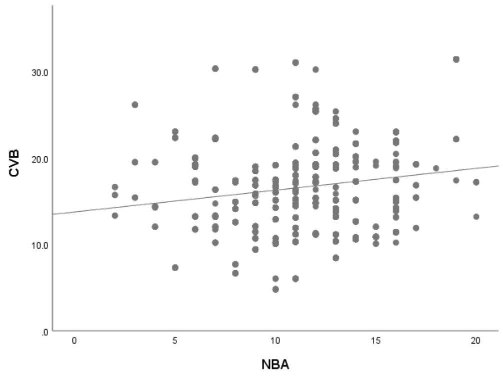


Figure B.4 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between number born alive (NBA) and within-litter birth weight variation (CVB) for parity 1 ($R^2 = 0.022$)

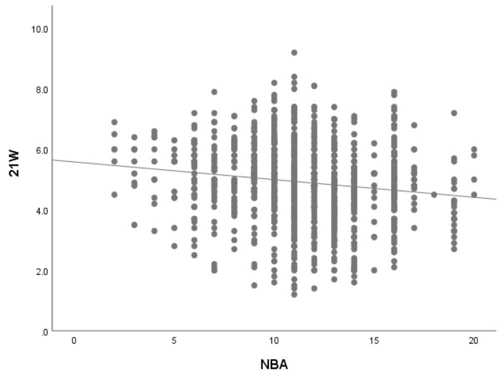


Figure B.5 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between number born alive (NBA) and individual 21 day weight (21W) for parity 1 ($R^2 = 0.022$)

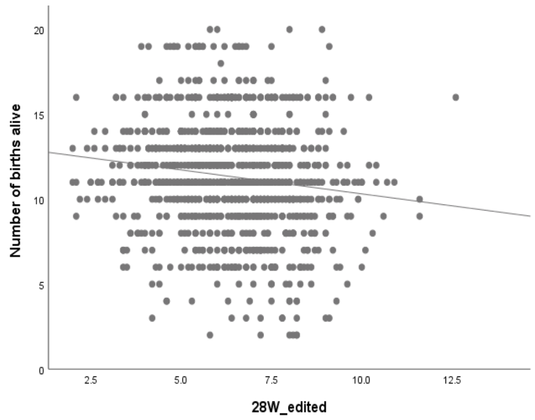


Figure B.6 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between number born alive (NBA) and individual weaning weight (28W) for parity 1 ($R^2 = 0.019$)

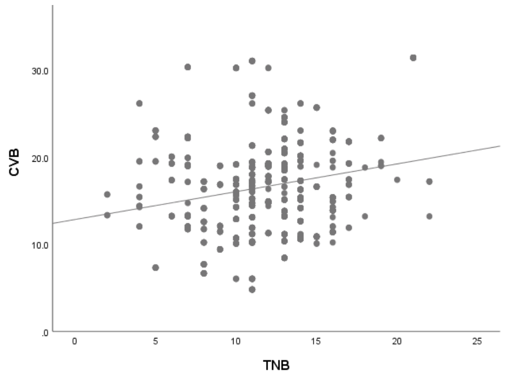


Figure B.7 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between total number born (TNB) and within-litter birth weight variation (CVB) for parity 1 ($R^2 = 0.037$)

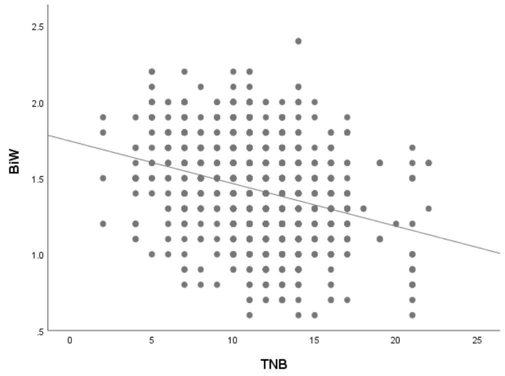


Figure B.8 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between total number born (CVB) and individual birth weight (BiW) for parity 1 ($R^2 = 0.084$)

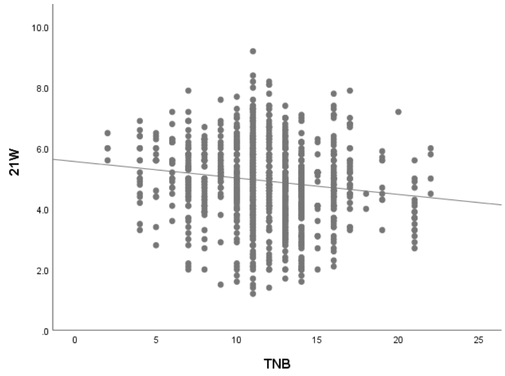


Figure B.9 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between total number born (TNB) and individual 21 day weight (21W) for parity 1 ($R^2 = 0.019$)

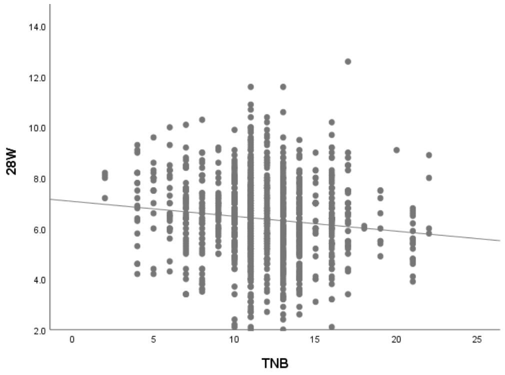


Figure B.10 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between total number born (TNB) and individual weaning weight (28W) for parity 1 ($R^2 = 0.015$)

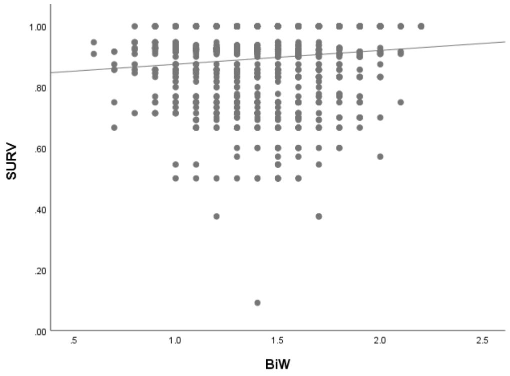


Figure B.11 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between survival to weaning (SURV) and individual birth weight (BiW) for parity 1 ($R^2 = 0.012$)

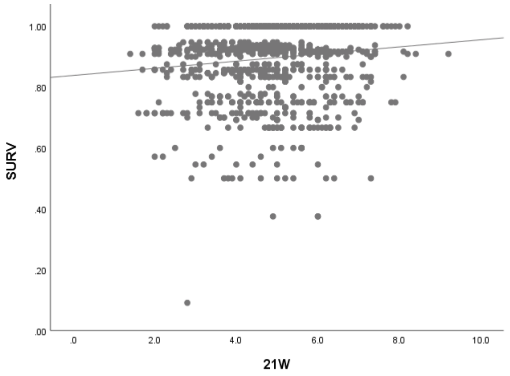


Figure B.12 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between survival to weaning (SURV) and individual 21 day weight (21W) for parity 1 ($R^2 = 0.015$)

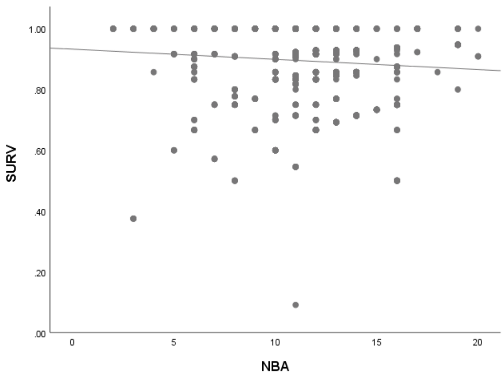


Figure B.13 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between survival to weaning (SURV) and number born alive(NBA) for parity 1 ($R^2 = 0.008$)

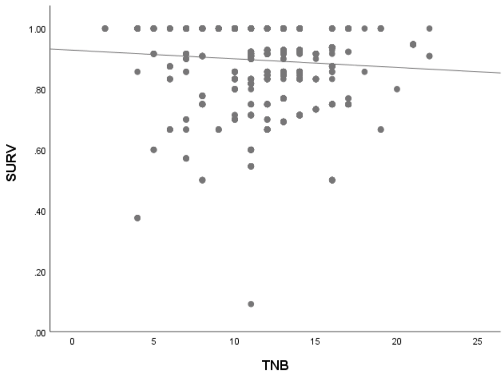


Figure B.14 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between survival to weaning (SURV) and total number of births (TNB) for parity 1 ($R^2 = 0.006$)

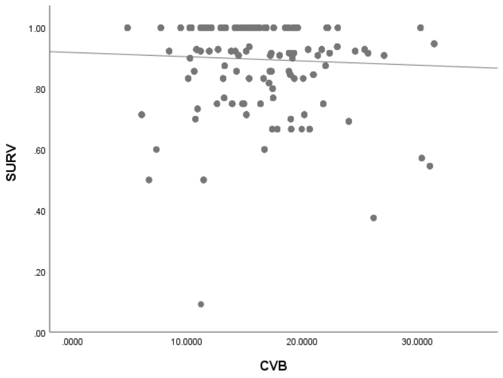


Figure B.15 Scatter plot illustrating the Pearson correlation ($p < 0.05$) between survival to weaning (SURV) and within-litter birth weight variation (CVB) for parity 1 ($R^2 = 0.004$)

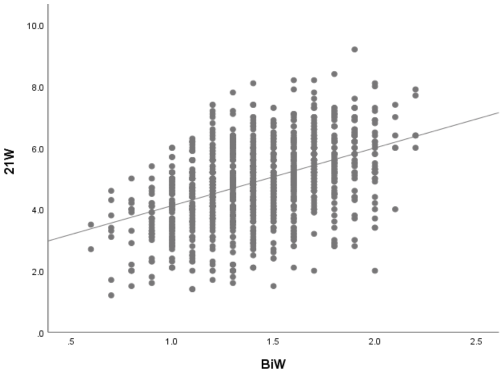


Figure B.16 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between individual 21 day weight (21W) and individual birth weight (BiW) for parity 1 ($R^2 = 0.194$)

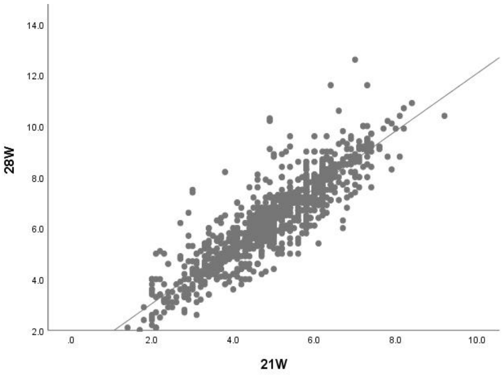


Figure B.17 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between individual weaning weight (28W) and individual 21 day weight (21W) for parity 1 ($R^2 = 0.780$)

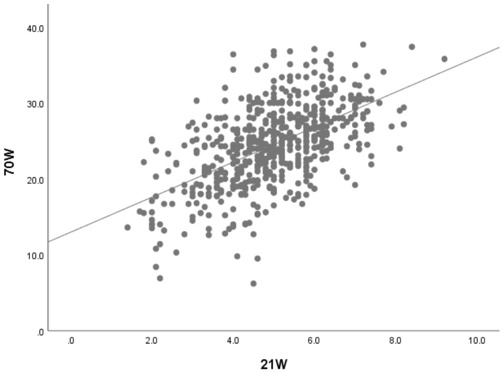


Figure B.18 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between individual 70 day weight (70W) and individual 21 day weight (21W) for parity 1 ($R^2 = 0.321$)

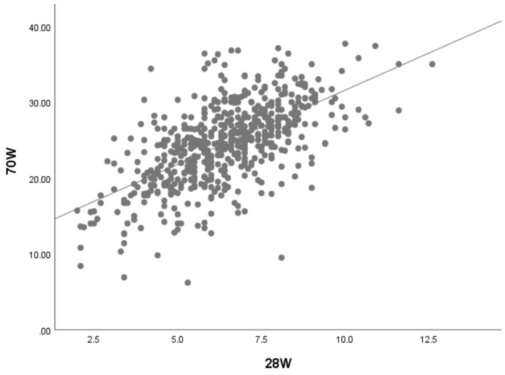


Figure B.19 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between individual 70 day weight (70W) and individual weaning weight (28W) for parity 1 ($R^2 = 0.376$)

Addendum C: Parity 2

Table C.1 LS means ±SE depicting the influence of piglet sex on performance traits for parity 2

Trait	Sex	
	Boar	Gilt
BiW (kg)	1.59±0.01^{a}	1.52±0.02^{b}
21W (kg)	5.80±0.06^{a}	5.51±0.06^{b}

BiW = individual birth weight, 21W = individual 21 day weight

$^{a, b, c}$ – Denote significant differences between means within fixed effects in rows ($p < 0.05$)

Table C.2 LS means ±SE depicting the influence of farrowing room on performance traits for parity 2

Trait	Farrowing Room				
	A	B	C	D	E
SURV (%)	0.87±0.01^{b}	0.92±0.00^{a}	0.92±0.00^{a}	0.92±0.01^{a}	0.88±0.01^{b}

BiW = individual birth weight, CVB = coefficient of variation for birth weight, SURV = survival to weaning

$^{a, b, c, d}$ – Denote significant differences between means within fixed effects in rows ($p < 0.05$)

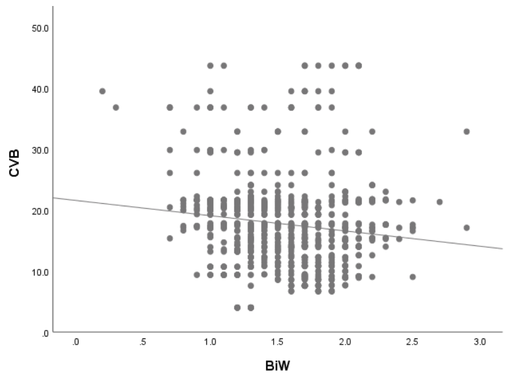


Figure C.1 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between within-litter birth weight variation (CVB) and individual birth weight (BiW) for parity 2 ($R^2 = 0.017$)

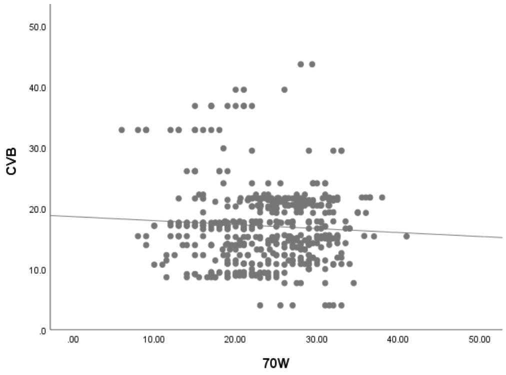


Figure C.2 Scatter plot illustrating the Pearson correlation ($p < 0.05$) between within-litter birth weight variation (CVB) and individual 70 day weight (70W) for parity 2 ($R^2 = 0.004$)

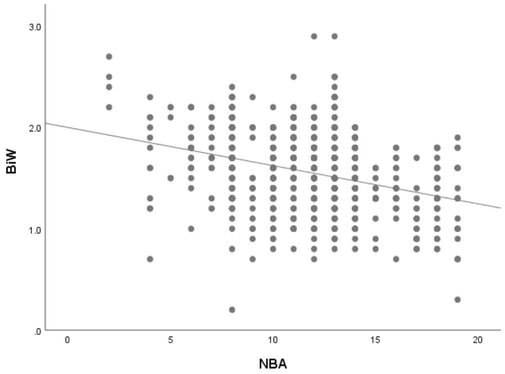


Figure C.3 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between number born alive (NBA) and individual birth weight (BiW) for parity 2 ($R^2 = 0.101$)

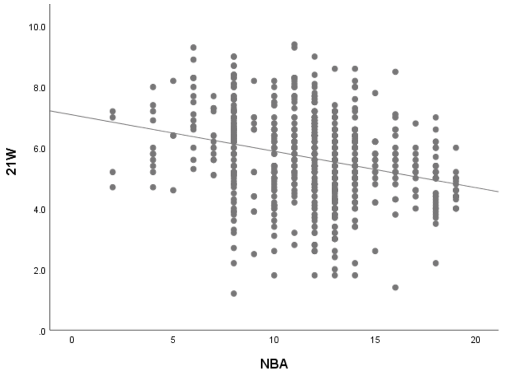


Figure C.4 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between number born alive (NBA) and individual 21 day weight (21W) for parity 2 ($R^2 = 0.079$)

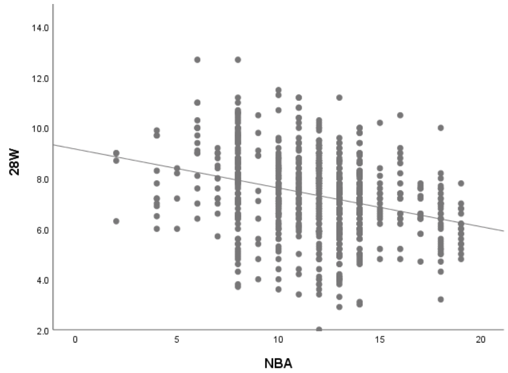


Figure C.5 Scatter plot illustrating the Pearson correlation ($p < 0.05$) between number born alive (NBA) and individual weaning weight (28W) for parity 2 ($R^2 = 0.092$)

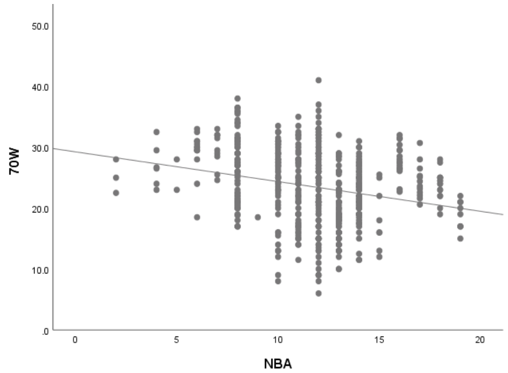


Figure C.6 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between number born alive (NBA) and individual 70 day weight (70W) for parity 2 ($R^2 = 0.059$)

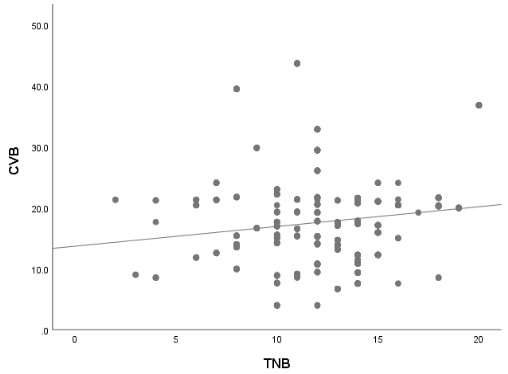


Figure C.7 Scatter plot illustrating the Pearson correlation ($p < 0.05$) between total number born (TNB) and within-litter birth weight variation (CVB) for parity 2 ($R^2 = 0.037$)

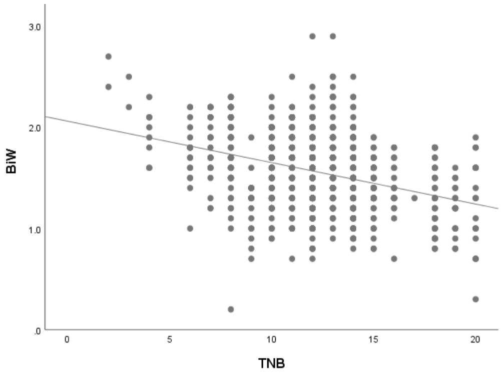


Figure C.8 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between total number born (TNB) and individual birth weight (BiW) for parity 2 ($R^2 = 0.119$)

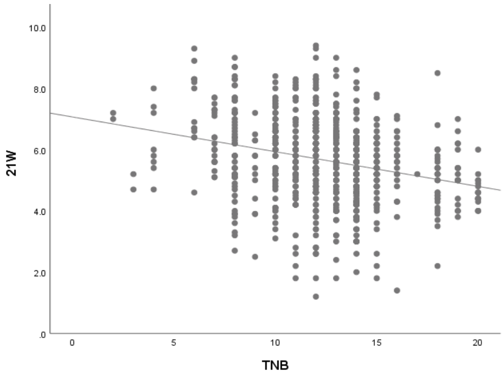


Figure C.9 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between total number born (TNB) and individual 21 day weight (21W) for parity 2 ($R^2 = 0.071$)

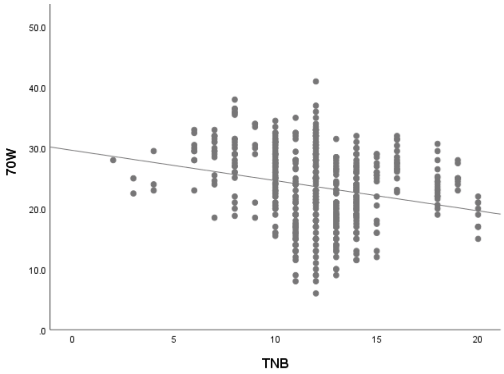


Figure C.10 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between total number born (TNB) and individual 70 day weight (70W) for parity 2 ($R^2 = 0.058$)

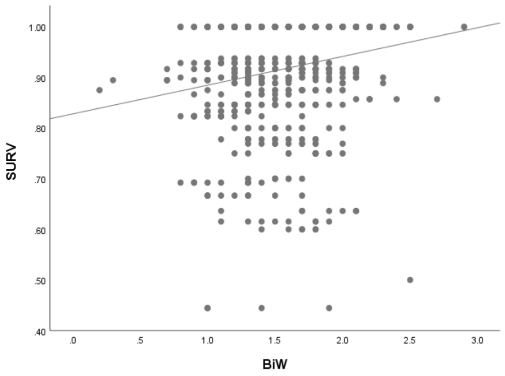


Figure C.11 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between survival to weaning (SURV) and individual birth weight (BiW) for parity 2 ($R^2 = 0.041$)

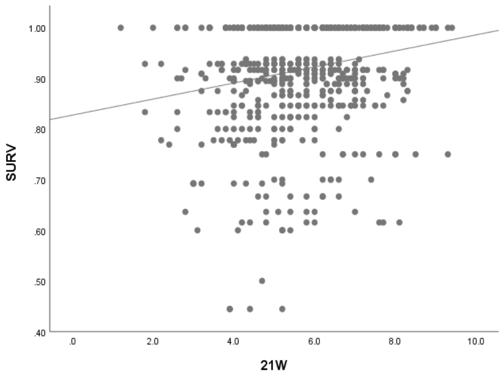


Figure C.12 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between survival to weaning (SURV) and individual 21 day weight (21W) for parity 2 ($R^2 = 0.040$)

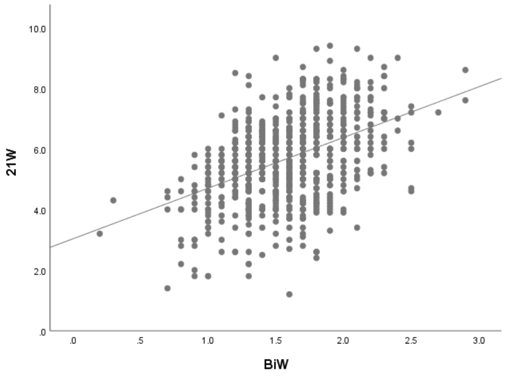


Figure C.13 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between individual 21 day weight (21W) and individual birth weight (BiW) for parity 2 ($R^2 = 0.209$)

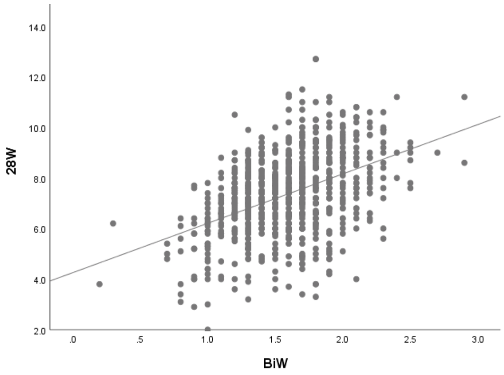


Figure C.14 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between individual weaning weight (28W) and individual birth weight (BiW) for parity 2 ($R^2 = 0.199$)

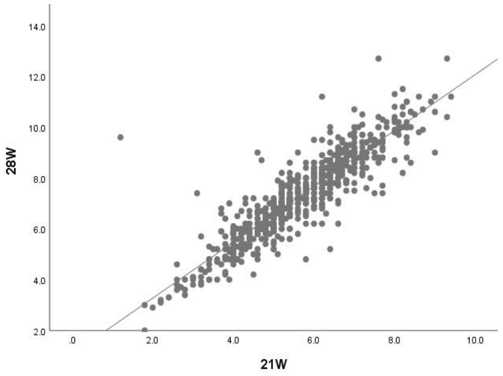


Figure C.15 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between individual weaning weight (28W) and individual 21 day weight (21W) for parity 2 ($R^2 = 0.805$)

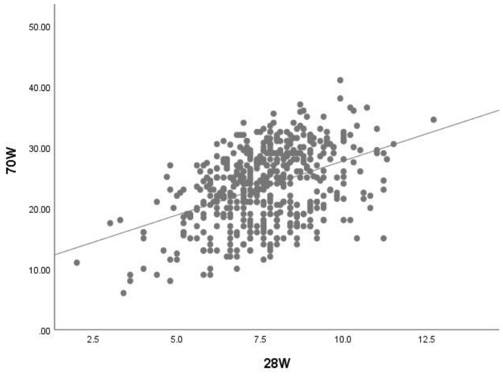


Figure C.16 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between individual 70 day weight (70W) and individual weaning weight (28W) for parity 2 ($R^2 = 0.189$)

Addendum D: Parity 3

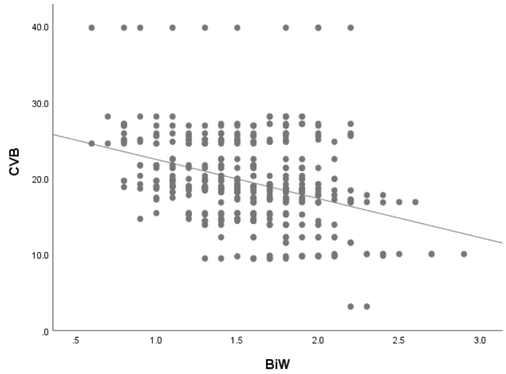


Figure D.1 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between within-litter birth weight variation (CVB) and individual birth weight (BiW) for parity 3 ($R^2 = 0.116$)

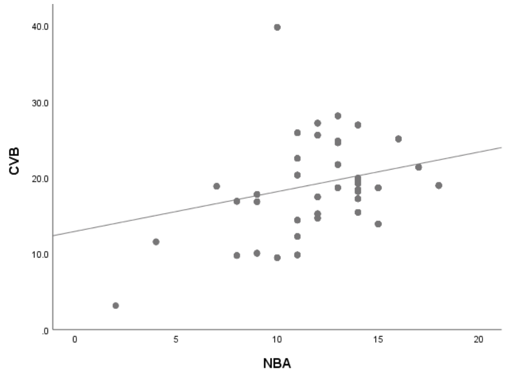


Figure D.2 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between number born alive (NBA) and within-litter birth weight variation (CVB) for parity 3 ($R^2 = 0.055$)

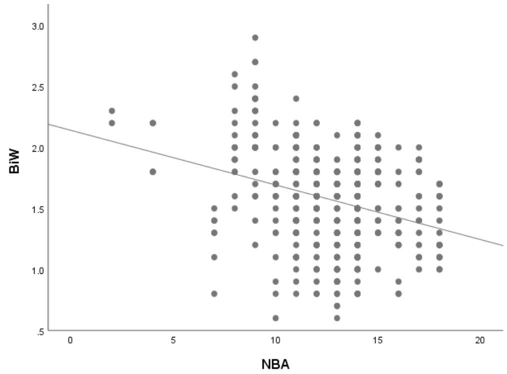


Figure D.3 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between number born alive (NBA) and individual birth weight (BiW) for parity 3 ($R^2 = 0.092$)

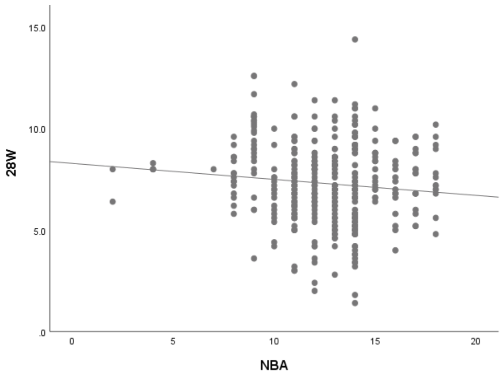


Figure D.4 Scatter plot illustrating the Pearson correlation ($p < 0.05$) between number born alive (NBA) and individual weaning weight (28W) for parity 3 ($R^2 = 0.011$)

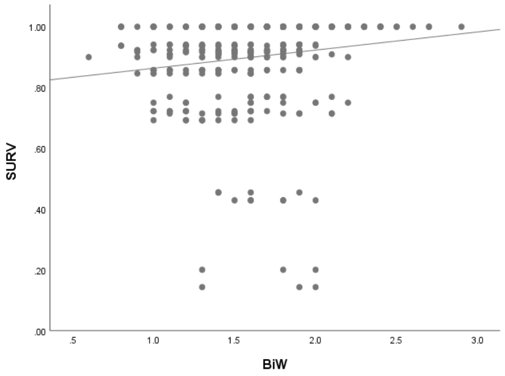


Figure D.5 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between survival to weaning (SURV) and individual birth weight (BiW) for parity 3 ($R^2 = 0.022$)

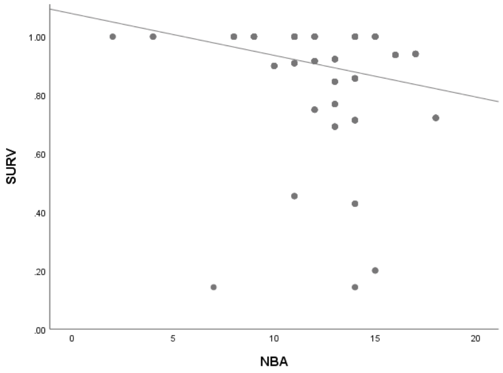


Figure D.6 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between survival to weaning (SURV) and number born alive (NBA) for parity 3 ($R^2 = 0.061$)

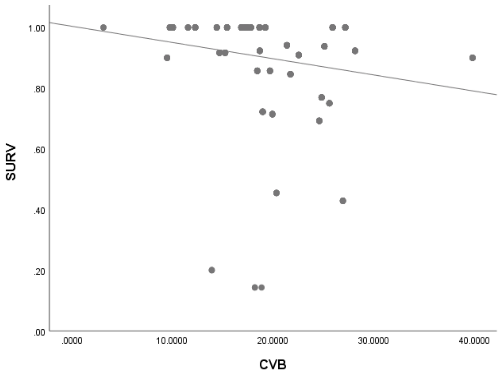


Figure D.7 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between survival to weaning (SURV) and within-litter birth weight variation (CVB) for parity 3 ($R^2 = 0.045$)

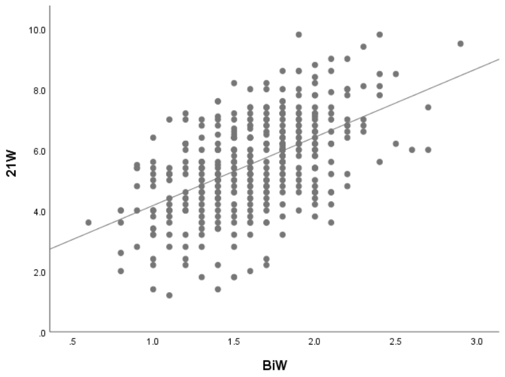


Figure D.8 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between individual 21 day weight (21W) and individual birth weight (BiW) for parity 3 ($R^2 = 0.291$)

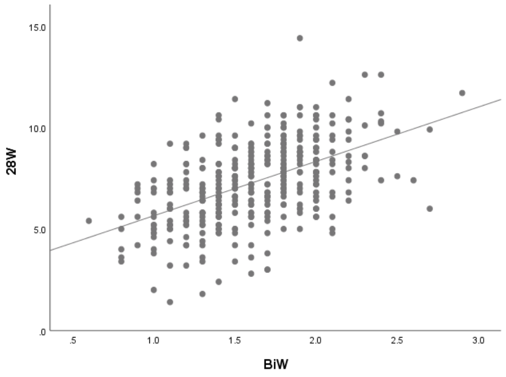


Figure D.9 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between individual weaning weight (28W) and individual birth weight (BiW) for parity 3 ($R^2 = 0.264$)

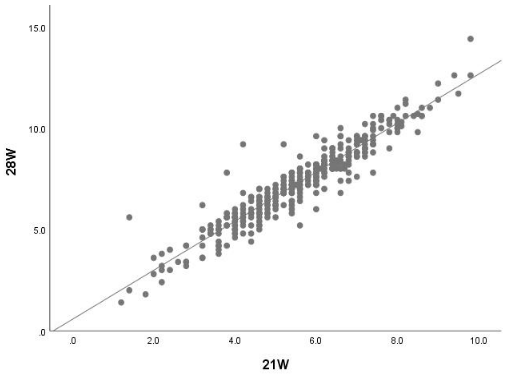


Figure D.10 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between individual weaning weight (28W) and individual 21 day weight (21W) for parity 3 ($R^2 = 0.897$)

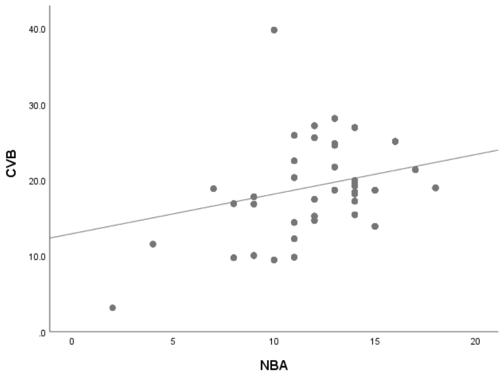


Figure D.11 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between within-litter birthweight variation (CVB) with number born alive (NBA) for parity 3 ($R^2 = 0.055$)

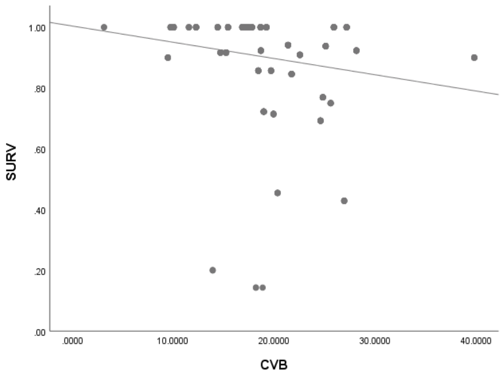


Figure D.12 Scatter plot illustrating the Pearson correlation ($p < 0.01$) between survival to weaning (SURV) with within-litter birthweight variation (CVB) for parity 3 ($R^2 = 0.045$)

Addendum E: Cross-parity analyses

Table E.1 LS means ±SE depicting the influence of parity on performance traits

Trait	Parity		
	1	2	3
TNB	11.84±0.08^{b}	12.29±0.10^{a}	NT
NBA	11.37±0.08^{c}	11.75±0.10^{b}	12.63±0.13^{a}
BiW (kg)	1.41±0.01^{b}	1.56±0.01^{a}	1.57±0.02^{a}
CVB	16.58±0.14^{c}	17.69±0.17^{b}	19.53±0.27^{a}
21W (kg)	4.91±0.04^{b}	5.67±0.04^{a}	5.59±0.07^{a}
28W (kg)	6.36±0.04^{b}	7.33±0.05^{a}	7.34±0.09^{a}
SURV (%)	0.89±0.00^{b}	0.92±0.00^{a}	0.89±0.01^{b}

NBA = number born alive, TNB = total number born, BiW = individual birth weight, CVB = coefficient of variation of piglet birth weight, 21W = individual 21 day weight, 28W = individual 28 day weight, SURV = survival to weaning, NT = not tested

$^{a, b, c}$ – Denote significant differences between means within fixed effects in rows (p <0.05)

Table E.2 LS means ±SE depicting the influence of parity x dam breed interaction on performance traits across parities

Trait	Parity								
	1			2			3		
	Duroc	Landrace	Large White	Duroc	Landrace	Large White	Duroc	Landrace	Large White
TNB	10.43 ±0.15^{c}	12.65 ±0.13^{ab}	12.11 ±0.13^{b}	10.33 ±0.19^{c}	12.87 ±0.15^{a}	13.16 ±0.17^{a}	NT	NT	NT
NBA	9.88 ±0.15^{c}	12.25 ±0.13^{ab}	11.63 ±0.13^{b}	9.81 ±0.19^{c}	12.49 ±0.15^{a}	12.42 ±0.17^{ab}	13.09 ±0.30^{a}	12.20 ±0.21^{a}	12.80 ±0.20^{a}
BiW (kg)	1.54 ±0.02^{ed}	1.38 ±0.01^{bf}	1.35 ±0.01^{b}	1.64 ±0.02^{ad}	1.62 ±0.02^{ad}	1.41 ±0.02^{bcf}	1.54 ±0.03^{acde}	1.71 ±0.03^{a}	1.48 ±0.02^{ef}
CVB	16.61 ±0.31^{cd}	15.65 ±0.27^{d}	17.56 ±0.26^{c}	17.34 ±0.39^{cd}	17.72 ±0.32^{c}	17.95 ±0.35^{c}	24.13 ±0.62^{a}	16.25 ±0.44^{cd}	20.32 ±0.41^{b}
21W (kg)	4.95 ±0.07^{b}	4.74 ±0.07^{b}	5.06 ±0.06^{bc}	5.75 ±0.09^{a}	5.66 ±0.07^{a}	5.60 ±0.08^{a}	5.86 ±0.16^{a}	5.52 ±0.11^{ac}	5.54 ±0.11^{ac}
SURV (%)	0.88 ±0.01^{d}	0.90 ±0.01^{bd}	0.90 ±0.01^{bd}	0.89 ±0.01^{bd}	0.95 ±0.01^{ac}	0.89 ±0.01^{d}	0.80 ±0.01^{e}	0.94 ±0.01^{ab}	0.88 ±0.01^{cd}

TNB = total number born, NBA = number born alive, BiW = individual birth weight, 28W = individual 28 day weight, SURV = survival to weaning, NT = not tested

$^{a, b, c}$ – Denote significant differences between means within fixed effects in rows (p <0.05)

Table E.3 LS means ±SE depicting the influence of parity x sire breed interaction on performance traits across parities

Trait	Parity								
	1			2			3		
	Duroc	Landrace	Large White	Duroc	Landrace	Large White	Duroc	Landrace	Large White
TNB	10.23 ±0.15^{d}	11.89 ±0.13^{c}	12.85 ±0.12^{b}	10.79 ±0.18^{d}	11.89 ±0.17^{c}	13.83 ±0.16^{a}	NT	NT	NT
NBA	9.66 ±0.15^{c}	11.33 ±0.13^{b}	12.52 ±0.12^{a}	10.27 ±0.18^{c}	11.38 ±0.17^{b}	13.26 ±0.16^{a}	12.34 ±0.24^{ab}	12.75 ±0.20^{a}	12.78 ±0.25^{a}
BiW (kg)	1.54 ±0.02^{ab}	1.36 ±0.01^{b}	1.37 ±0.01^{b}	1.62 ±0.02^{a}	1.62 ±0.02^{a}	1.45 ±0.02^{bc}	1.61 ±0.03^{a}	1.52 ±0.02^{ac}	1.63 ±0.03^{a}
CVB	16.27 ±0.27^{b}	17.30 ±0.23^{bc}	16.16 ±0.22^{b}	16.87 ±0.32^{ab}	17.32 ±0.30^{b}	18.68 ±0.28^{ac}	20.17 ±0.49^{a}	20.28 ±0.42^{a}	17.71 ±0.51
70W (kg)	23.75 ±0.37^{a}	24.90 ±0.32^{a}	24.44 ±0.32^{a}	25.00 ±0.38^{a}	21.99 ±0.34^{b}	23.92 ±0.35^{a}	NT	NT	NT
SURV(%)	0.86 ±0.01^{bc}	0.89 ±0.00^{ab}	0.91 ±0.00^{b}	0.91 ±0.01^{a}	0.92 ±0.01^{a}	0.91 ±0.01^{a}	0.82 ±0.01^{c}	0.92 ±0.01^{a}	0.90 ±0.01^{ab}

TNB = total number born, NBA = number born alive, BiW = individual birth weight, CVB = coefficient of variation of piglet birth weight, 70W = individual 70 day weight, SURV = survival to weaning, NT = not tested

$^{a, b, c}$ – Denote significant differences between means within fixed effects in rows ($p < 0.05$)

Table E.4 LS means ±SE depicting the influence of parity x period of birth interaction on performance traits

Trait	Parity 1				Parity 2			
	Spr16	Su16	Su17	Aut17	Spr17	Su17	Aut17	Wint17
TNB	11.68±0.14^{b}	12.07±0.19	11.61±0.13^{b}	12.35±0.19	12.26±0.39	13.38±0.34^{a}	11.86±0.14^{b}	12.58±0.16^{a}
NBA	11.26±0.14	11.96±0.19	10.91±0.13	11.89±0.18	11.37±0.38	13.14±0.33	11.31±0.14	12.04±0.16

Spr16 = Spring 2016, Su16 = Summer 2016, Su17 = Summer 2017, Aut17 = Autumn 2017, Wint17 = Winter 2017, TNB = total number born, NBA = number born alive

$^{a, b, c}$ – Denote significant differences between means within fixed effects in rows ($p < 0.05$)