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Estimation of (co)variance components and genetic parameters for litters per sow per year and pigs weaned per sow per year

by

Nattakorn Sujipittham

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

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2007

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ABSTRACT

Increasing the number of pigs weaned per sow per year is an economically important goal for pig producers. This study was conducted to estimate (co)variance components and genetic parameters of pigs weaned per sow per year (PWSY) and litters per sow per year (LSY), and then determine the possibility of direct selection for improving both traits. Data analyzed were from 11,283 sows from three herd groups, which included 1,925 sows from a purebred herd in Thailand, and 9,358 sows from two purebred/crossbred herd groups in the United States over a time period ending in March 2007. The distribution of both traits was considered to be normally distributed, based on the shape of the normal curve of each trait in each herd group. The (co)variance components, heritabilities, and genetic correlations for each trait were estimated using Restricted Maximum Likelihood (REML) bivariate animal model analysis. The animal model for LSY and PWSY contained fixed effects for breed, parity, and year-month of farrowing (contemporary group). Estimates of heritability ($h^2$) for LSY were low and quite similar, with the values between 0.09 and 0.18 across the three herd groups. The heritability estimates ($h^2$) for PWSY were low to moderate around 20 percent across the three herd groups. The estimated genetic correlation of LSY with PWSY was high and favorable, ranging from 0.45 to 0.70 across purebred and crossbred herds. The opportunity to make permanent genetic improvement by including LSY and PWSY in the selection program appears to be possible because the heritability of LSY and PWSY was low to moderate, and genetic correlation between two traits was favorable. Therefore, selection for genetic improvement in LSY or PWSY appears possible and should complement each other.
CHAPTER 1. INTRODUCTION

In modern swine production, several traits are used as benchmarks by swine producers to estimate reproductive efficiency. One of the most economically important aspects of reproductive efficiency is the number of pigs weaned per sow per year (PWSY). The number of PWSY is a function of litter size born alive, pre-weaning mortality (resulting in the number of pigs weaned per litter), and litters farrowed per sow per year (LSY). The number of LSY is influenced by gestation length, lactation length, and nonproductive days (NPD) (Dial et al., 1992). In general, NPD accumulate for the total number of days in which breeding females are neither gestating nor lactating, including unsuccessful farrowing (Wilson et al., 1986). Moreover, NPD accumulation directly impact herd productivity (number of litters per female and piglets produced) and profitability where an increase in NPD for every 10 days is expected to cost the farm $12.50 to $17.50 (Peet, 2004; Bates, 2005). Swine breeding herds with lower NPD tend to have greater herd productivity in terms of LSY and PWSY. A previous study reported that every 10 day decrease in NPD would increase LSY by 0.07 litters and PWSY by 0.03 piglets (Koketsu, 2005a). Therefore minimizing NPD will tend to increase LSY and PWSY.

LSY is also one of the important variables determining financial efficiency, especially farm asset turnover as there is a great opportunity to decrease the cost per piglet by increasing the number of LSY. According to PigCHAMP (1996), LSY is expressed as a proportion of total gestation days to total breeding female days in a period of a year. The total gestation days will count only the sows having a successful gestation, and the total breeding female days will accumulate from the first entry until removal of inventoried gilts and sows from the herd. The economic impact of an increase or decrease in LSY varies widely and is
difficult to measure. However, the cost of NPD per sow can be calculated from variable costs, (primarily feed and labor) and fixed costs (including building, depreciation, and interest) (Shaw, 2005). There is also an opportunity cost as a non-productive sow day fails to produce a market animal that can be sold at a profit.

The major components of NPD are farrowing rate and the intervals of entry to first service, weaning to service, and weaning to removal. Weaning to service and weaning to estrus intervals are measurable and heritable traits (Ten Napel et al., 1995). Previous research has reported that the prolonged intervals of weaning to estrus (WEI) and weaning to service (WSI) impacts sow productivity and reproductive efficiency, for example the number of piglets born alive and weaned litter weight (Tholen et al., 1996; Hanenberg et al., 2001; Holm et al., 2004). The variations of WEI and WSI, which are major components of NPD, are considered to be influenced more by environmental factors than genetic factors. Heritability estimated of WEI and WSI ranges from zero to 0.24 (Fahmy et al., 1979; Ten Napel et al., 1995; Adamec and Johnson, 1997; Ehlers et al., 2005). Even though heritabilities of WEI and WSI are quite low, improvement by selection for reducing both intervals can be achieved by using Best Linear Unbiased Prediction (BLUP) based selection program (Rydmer, 2000; Ten Napel et al., 1995).

Indirect selection for increasing LSY and PWSY could be accomplished by reducing a component of NPD, i.e. weaning to estrus interval or weaning to service interval. However, improvement in reproductive efficiency by directly selecting for LSY or PWSY has not yet been studied in depth. It may be possible to make a permanent genetic improvement in LSY and PWSY traits if these traits are found to be appropriate for making genetic improvement. To accomplish the assumption, the collection of data must be an accurate measurement.
Secondly, the distribution of the traits should be normal. Thirdly, the traits should have an adequate heritability. Fourthly, genetic correlation between traits should not be undesirable. Therefore, the objectives of this study were to examine the above points, estimate the variance components (using BLUP based selection) and resulting genetic parameters for LSY along with PWSY, using both purebred and crossbred data.
CHAPTER 2. LITERATURE REVIEW

Reproductive Efficiency

One of the main objectives of swine production is to maximize the output of pigs produced from a breeding herd at a minimum of cost. Several of the factors that influence achieving these objectives, relate to overall sow productivity. Herd reproductive performance is one way to measure sow productivity and a major factor in economical production. Farrowing rate, non productive sow days (NPD), litters per sow per year (LSY) and pigs weaned per sow per year (PWSY) are the important indicators used to measure reproductive performance and financial efficiency of herd.

PWSY, one of the most economically important traits, is determined by the number of litters per sow per year (LSY) and pigs weaned per sow as shown in Figure 1 (Holden and Ensminger, 2005; NPB, 2005). Previous studies have reported that PWSY has strong positive correlations with LSY and PWL (from 0.57 to 0.89 and 0.71 to 0.89, respectively) (Wilson et al., 1986; Stein et al., 1990b; Van Til et al., 1991; Koketsu, 2002). However, no relationship between LSY and PWL was found (Wilson et al., 1986; Koketsu, 2000a). Therefore, the potential to maximize the number of PWSY by increasing the LSY might be achieved.

Improvement in reproduction in swine has primarily focused on making genetic and management improvements in component traits such as total born per litter, number born alive per litter, and in some cases, reducing pre-weaning piglet mortality. Efforts to make genetic improvement by selecting directly on LSY or PWSY have not been reported in the literature.
Figure 1. Factors influencing pigs weaned per sow per year

Litters farrowed per sow per year

The average number of litters per sow per year (LSY) is an essential measure of reproductive efficiency in a breeding female herd. Historically it has been calculated from the number of farrowings taking place during a year divided by the average number of sow inventory in the herd during the period (Wilson et al., 1986; Van Til et al., 1991).

Historically within the swine industry, it is generally accepted that a LSY target of 2.3 or better is appropriate. However, several studies found that the average LSY was below this target value (Van Til et al., 1991; Koketsu, 2000a, and 2002). According to Table 1, the average LSY was found between 2.11 and 2.30 litters in the North America (Wilson et al., 1986; Stein et al., 1990b; King et al., 1998; Lucia et al., 2000b). In the Japanese study, Koketsu (2005a) examined herd-management factors associated with non productive sow days, (NPD) of 124 farms. The average of LSY was approximately 2.28 litters.
The primary traits that are involved in LSY include entry to first service interval, subsequent farrowing, gestation length, lactation length, weaning to service interval (with all the latter traits involved in each parity of the sow), followed by either cull to removal interval or mortality rate. In the NPB Production and Financial Standards, a breeding female day was defined as any day from entry of the female into herd inventory until removal of the female from the herd for any reason (NPB, 2002). This is because the female accumulates costs during these days. A product is produced only when a litter is farrowed from a successful gestation. Therefore, LSY has been defined as the sum of gestation days in a defined period of time divided by the sum of breeding female days in that same period of time, on an annualized basis (PigCHAMP, 1996).

\[
\text{LSY} = \frac{\text{Sum of gestation days in period}}{\text{Sum of breeding female days in period}} \times \frac{365}{115}
\]

It appears that farrowing rate is the factor that can primarily influence LSY, with NPD and lactation length or weaning age of piglets being other significant factors that can improve LSY. Gestation length does not appear to significantly influence LSY due to a nearly constant level of 113-115 days (Dial et al., 1992). Therefore, to increase the number of LSY, farrowing rate must first be maximized, and then both the lactation length and NPD hold opportunity to increase LSY (Wilson et al., 1986; Stein et al., 1990b).
Components of litters per sow per year

Non productive sow days

A factor having the most important influence on the number of LSY is the average number of non productive sow days (NPD), defined as the days when a breeding female is neither gestating nor lactating during a year (Wilson et al., 1986). NPD is primarily influenced by farrowing rate, weaning-to-conception interval, and weaning to culling interval (Van Til et al., 1991). Several studies reported that NPD in North America ranged from 50 to 70 days per year (Wilson et al., 1986; Stein et al., 1990b; Lucia et al., 2000a and 2000b; Koketsu, 2005b).

NPD are accumulated from the beginning to the end of the lifetime production of a sow. According to Dial et al. (1992) and Shaw (2005), NPD can be separated into three major categories, which are influenced by different management factors and genetic factors. First, pre-service intervals, the period that a female waits to be mated, are the gilt entry to service interval and weaning to first service interval in sows. Second, post-weaning intervals, the period between successful service and the time from service until female, are detected as not pregnant. These are the intervals such as mating to return and mating to unsuccessful farrowing. Third, removal intervals, the period that a female was removed from the herd group, are for example entry to removal and unmated weaning to removal, unsuccessful farrowing to removal.

In a study by Koketsu (2005a), the six component intervals of nonproductive days of 95 pig breeding herds were examined. The average NPD was about 53.9 days (SD = 16.1; Table 1). Three component intervals (sow first-mating-to-culling interval, first-mating-to-pregnancy interval and weaning-to-first-mating interval) were indicated as approximately
76% of NPD. This study demonstrated that decreasing these component intervals were a key to increasing herd productivity. Studies reported that NPD and LSY shared a high negative correlation with coefficients ranging from -0.79 to -0.90 (Wilson et al., 1986; Stein et al., 1990b). Furthermore, Koketsu (2005a) reported that if NPD decreased by 10 days, the number of LSY would increase approximately by 0.07 and by 0.6 PWSY. Similarly, King et al. (1998) reported that decreased NPD by 0.3 days and increased multiple mating by 1% tended to increase LSY by 0.021 litters, and PWSY by 0.03 pigs. Therefore, reducing NPD is the best way to improve herd productivity by maximizing LSY (Wilson et al., 1986; Lucia et al., 2000b).

Tantasuparuk et al. (2001b) suggested that efficient farm management and production strategies were essential in order to control the herd NPD. For example, accurate heat detection, effective boar stimulation, meeting nutrition requirements and excellent gilt pool management can be fundamental to control pre-service intervals. Also, market strategies for culling an inefficient breeding female could impact weaning to removal interval (Koketsu et al., 1996; Koketsu, 2005a).

**Lactation length**

Lactation length, defined as the days that breeding females are lactating, are considered as productive days. Lactation length of the sows (or weaning age of the piglets) affects sow reproductive performance and measures of productivity. Currently, the US swine industry tends to wean the litters from sows at between 17 to 22 days (Koketsu et al., 1997a; King et al., 1998; Koketsu 2005b). In the European swine industry, lactation length is sometimes limited at a minimum of 28 days due to animal welfare legislation (Tummaruk et al., 2000a and 2000b; Gaustad-Aas et al., 2004). It has been shown that reduced lactation
period tended to increase LSY and PWSY (Xue et al., 1993; Mabry et al., 1996). Lactation length is normally a management decision, with no genetic component.

King et al. (1998) reported that shorter lactation length was associated with shorter farrowing interval, greater LSY and higher PWSY. The LSY and PWSY were increased by 0.02 litters and 0.18 pigs, respectively as lactation length was decreased by one day. However, very early weaning or short lactation length (less than 14 days) can negatively affect subsequent reproduction. Xue et al. (1993) and Dial (1995) reported that the intervals of weaning to estrus, weaning to service and weaning to conception increased with a decrease in lactation period below 14 days.

In an American study, Xue et al. (1993) analyzed a data base including 14,925 records from 39 sow herds in order to examine the relationships between lactation length and subsequent reproductive performance. Their findings indicated that the reduction of the lactation length was important to increase the frequency of farrowing or litters per sow per year (LSY). Short lactation length resulted in long WSI and later high NPD accumulation. The study also found that the weaning to first service interval increased quickly as the lactation length was below 17 days. Nevertheless, there were no significant differences between WSI of the 21-day lactation group and the higher groups (P > 0.05).

Similarly, Clowes et al. (2006) analyzed a PigCHAMP database of 33,000 sows from across the United States-Canada pig industry from the years 2000 to 2005. The authors evaluated the benefit to sow performance as lactation length varied from 11 days to 21 days. The proportion of sows that had WSI less then 7 days was increased from 47% to 72%, when lactation period increased from 11-12 days to 18-21 days. Furthermore, the proportion of sows bred was up to 87% when lactation length was longer from 14 to 21 days.
In addition, Mabry et al. (1996) examined the effect of lactation length on WSI and first service farrowing rate by using 178,519 litter records from purebred and crossbred sows. In their study, the shorter lactation length was associated with the longer WSI. Besides, WSI was increased as lactation length was less than 22 days or greater than 27 days. Those sows which have a lactation length longer than 12-14 days would have a significantly higher first service farrowing rate when compared to sows with a lactation length less than 12-14 days. However, parity 1 sows would need to have at least a 14 day lactation and parity 2 sows would need to have at least a 12 day lactation in order to maintain their recycle in average of seven days or less.

In a European study, Tummaruk et al. (2000b) investigated the effect of WSI and prolonged lactation length on subsequent reproductive performance of 6,989 Swedish Landrace and Yorkshire sows. They reported that increasing lactation length of 1 week could decrease in WSI of about 0.2 day. A prolonged lactation length of 4, 5, 6 and 7-8 weeks caused a significantly reduced weaning to service interval (WSI) of 5.8, 5.6, 5.4, and 5.2 days for both breeds. Landrace sows had a longer WSI of 0.3 day and Yorkshire sows increased 0.1 day when lactation decreased from 5 to 4 weeks.

**Farrowing rate**

Farrowing rate, the proportion of served females that farrow, is closely related to NPD (service to successful and unsuccessful interval; Dial et al., 1992). Typically, the accepted target of farrowing rate for improving economic efficiency in swine industry is 85% or higher (Koketsu, et al., 1997a). However, according to many research values, the average farrowing rate is lower than the target value, ranging from 72 to 85 percent. In North American herds, the farrowing rate was found to be between 75% and 85% (Hurtgen et al.,
1980; King et al., 1998; Koketsu, 2000a). In South American herds, average farrowing rate of 82.6 percent was cited by a study of Correa et al. (2002). In a tropical country, farrowing rate was between 75 and 80 percent in Thailand (Kunavongkrit et al., 2000; Tantasuparuk et al., 2000).

This variation of farrowing rate depends on parity distribution, genetics, previous lactation length, season, climate, and management (Koketsu et al., 1996; Tummaruk et al., 2000a). It has been demonstrated that different farrowing rates indicated different herd performance and productivity (Dial et al., 1992). Studies have shown that the high farrowing rate of high-performing herds can reduce NPD and increase LSY as well as PWSY (Koketsu et al., 1997a; King et al., 1998; Koketsu, 2002). A study of Stein et al. (1990b) indicated the phenotypic correlation between reproductive efficiency and farrowing rate. Farrowing rate and NPD were negatively correlated with a value of -0.54. On the other hand, the correlation of farrowing rate with LSY and PWSY was fairly moderate (0.51 and 0.45, respectively). This indicated that the breeding herd with a higher farrowing rate tended to also have shorter NPD, greater LSY, and greater PWSY.

**Weaning to service interval**

Weaning to service interval (WSI), one of the main components of NPD, may be affected by many factors such as previous lactation length, parity, lactation feed intake, temperature, and heat detection (Dial et al., 1992; Close and Cole, 2000; Tummaruk et al., 2000a; Thacker and Bilkei, 2005). In most herds, a breeding sow is expected to return to estrus and be re-served within 7 days after weaning. Weaned sows that do not express estrus quickly result in more NPD accumulation. In the United States, the average WSI was found to average 6.8 days in the high-performing herds (Koketsu, 2000a). In Europe, WSI was 5.9
± 2.5 days in Swedish herds (Tummaruk et al., 2000a). In Australia, Hughes (1998) reported the average WSI to be as low as 5.4 days. In tropical countries, WSI ranged from 5.9 to 7.7 days (Tantasuparak et al., 2000; Suriyasomboon et al., 2006).

It has been reported that the least non-productive days for service after weaning of sows were between 3 to 5 days (Ten Napel et al., 1995). A prolonged WSI, which is greater than day 7 post-weaning, has a negative impact on the subsequent reproductive performance. A study of Koketsu (1999) evaluated 9,192 mated sows during 0 to 6 days, 7 to 12 days, and 13 days or greater after weaning in the United States. They found that sows that were mated during 7 to 12 days after weaning had the lowest farrowing rate and total pigs born at subsequent farrowing (P < 0.01). Similarly, Tummaruk et al. (2000b) examined the effect of WSI associated with a subsequent farrowing rate in 6,089 Swedish Landrace and Yorkshire sows. They reported that subsequent farrowing rate decreased when sows were bred between 7 and 9 days after weaning. However, farrowing rate gradually increased as WSI increased from day 9 to day 20.

In general, the intervals between weaning to service (WSI) and weaning to estrus are similar despite a small different amount of variation (Adamec and Johnson, 1997). Poleze et al. (2006) examined the consequences of variation in weaning to estrus interval (WEI) on reproductive performance, comparing primiparous and multiparous sows. In their study, primiparous and multiparous sows which had WEI of 3-5 days in both classes had the highest farrowing rate (P < 0.05), when compared to sows which had WEI of 0-2, 6-8, 9-12 and 13-18 days. On the other hand, Correa et al. (2002) found both early and prolonged WEI had no influence (P < 0.05) on farrowing rate. Also, it has been reported that increasing feed intake
during lactation can reduce WEI and WSI after the first litter (Xue et al., 1993; Koketsu and Dial, 1997; Tantasuparuk et al, 2001a).

### Sow removal

A removed sow is defined as one that has been culled or died. High removal rates of sows from the herd can negatively impact breeding herd productivity (NPD, LSY, and PWSY; Dial et al., 1992) and herd profitability (Lucia et al., 2000a; Rodriguez-Zas et al., 2006). Four major reasons for removal (70% of all removals) are reproductive failure, poor performance, leg problems, and death (Stein et al., 1990a; Lucia et al., 2000b). Previous studies reported that the reasons for culling vary with parity from which the young parity sow was removed due to reproductive failure such as anestrus, failure to conceive, and unsuccessful farrowing (Koketsu et al., 1997b). A study of Engblom et al. (2006) reported that removal of young sows due to reproductive disorder had the highest number of NPD per parity and longest intervals from entry to removal. Lucia et al. (2000b) reported that culled young females had not only accumulated more NPD, but also produced a small number of weaned pigs per lifetime litter.

Sow death rate has been found to be related to NPD. Increasing sow mortality rate in a breeding herd is associated with increasing NPD which result in decreasing herd profitability (D’Allaire et al., 1993; Abiven et al., 1998). Studies found herd mortality rate ranging from 3 to 8% (Stein et al., 1990b; D’Allaire et al., 1993; Abiven et al., 1998; King et al. 1998; Koketsu, 2005a; Rodriguez-Zas et al., 2006). In a literature of Chagnon et al. (1991) and Koketsu (2000b), they reported the summer months of July, August, and September to have the highest sow mortality rate of 6 to 7%. The reasons of high mortality risk during summer could be explained by Chagon et al. (1991). It seems that heart failures, accidents of
abdominal organ, and cystis-pyelonephritis were the three major causes of death during a hot temperature. It seems also that reducing and controlling fluctuating temperature during a summer could decrease sow mortality rate.

**Breeding management effects on reproductive efficiency**

It has been established that many factors play an important role for reproductive success in a swine herd such as farrowing rate, weaning to service interval, NPD, litter size, LSY, and PWSY (Dial et al., 1992). To improve the reproductive performance such as WSI, farrowing rate, NPD, LSY, and PWSY in a breeding herd, producers and technicians should understand the basic concepts of reproduction and management such as boar contact, estrus detection, timing of insemination, and feed intake (Koketsu and Dial, 1997; Nissen et al., 1997; Tantasuparuk et al., 2000).

**Estrus detection and boar contact**

Accurate estrus detection and efficient boar contact are essential to decrease the gilt’s entry to service interval, and increase the probability of breeding females to be inseminated at the correct time relative to ovulation. It appears that boar contact influences the onset and expression of estrus due to LH change as well as olfactory, auditory and visual stimuli (Dial et al., 1992; Holden and Ensminger, 2005). The study of Langendijk et al. (2000) showed the importance of the boar detection during estrus detection. They examined the increasing intensity of estrus stimulation on estrus expression in weaned sows. Four groups of sows were evaluated by four increasing levels of stimulation every 8 hours. These stimulating levels were a back pressure alone by a technician, boar without back pressure, boar with a back pressure, and multiple boars with a back pressure. The duration of estrus from the four groups was 22, 29, 42 and 55 hours, respectively. The authors indicated that increasing
intensity of boar stimulation tended to increase the estrus standing of weaned sows. Their finding was in agreement with Dial et al. (1992), Pearce and Pearce (1992), and Tantasuparuk et al. (2000).

The increasing frequency of estrus detection in a day has been reported to increase the duration of estrus in weaned sows (Knox et al., 2002). Their experiment evaluated the effects of once, twice and three times daily boar exposure on reproductive weaned sow performance of 212 sows. The percentage of sows expressing estrus in 8 days was the highest for a group of once a day exposure compared to the other groups exposed to boars at high frequencies. In addition, the percentage inseminated within 24 hours before ovulation in the group of once daily exposure was lowest at 28% compared to twice and three times daily groups of 62% and 66%, respectively. Twice daily estrus stimulation also positively affected early puberty in gilts (Hughes et al., 1997) However, increasing frequency of the boar exposure did not reduce the weaning to estrus interval and repeat service rate (Knox et al., 2002). Additionally, Correa et al. (2002) compared the time period of first estrus detection between 8:30 a.m. and 5:00 p.m. Both times had no effect to WSI and farrowing rate.

Another study investigated the influence of weaned sows which were housed adjacent the boar (Knox et al., 2004). They found the negative effect of the boar’s housing nearby the weaned sows. In their study, boars which were housed close to weaned sows tended to lower 7-day WEI interval, and reduced duration of estrus by 12 hours compared to housing the boar away from weaned sows.

**Timing of insemination**

To achieve a high conception rate and litter size, mating strategies and timing of breeding should be considered (Colenbrander et al., 1993). Fundamentally, ovulation occurs
between 20 to 60 hours after the beginning of estrus which is initiated by LH surge (Whittemore, 1993). A study of Kemp and Soede (1996) evaluated the relationship among duration of estrus, onset-to-estrus-to-ovulation interval, and fertilization by using real-time ultrasound scanning of 201 multiparous sows. Optimal conception rate was found when inseminating from 0 to 24 hours of sows before ovulation. Similarly, Nissen et al. (1997) identified the optimal time of insemination related to ovulation of 143 multiparous crossbred sows. They found that the optimal interval time for insemination was from 28 hours before ovulation to 4 hours after ovulation. The small difference in the optimal mating time that was found between the two studies may be from the time intervals during ultrasound scans (Nissen et al., 1997). In primiparous sows, a study of Bortolozzo et al. (2005) reported that insemination less than 16 hours before ovulation resulted in reduced pregnancy rate and litter size.

Late insemination may have a detrimental effect on reproductive performance. A study of Castagna et al. (2003) was conducted with 789 sows from parity 2 to parity 12 in Brazil in order to determine the effect of late insemination on sow reproductive performance. Their study reported that low farrowing rate was influenced by late insemination. Similarly, other studies found the reproductive impact of late mating on young parity sows. Rozeboom et al. (1997) reported that farrowing rate of parity 1 and parity 2 sows was decreased approximately 22 percent due to late insemination. Therefore, the accuracy of the ovulation prediction and the appropriated insemination time must be considered in order to reach the optimal fertilization.
Feed intake

It has been documented that the role of nutrition during lactation, after weaning, and before and after ovulation, impacts to reproductive performance of the sow and overall productivity (Peltoniemi et al., 1999; Close and Cole, 2000). High levels of feed intake during short lactation periods positively influenced WSI, subsequent farrowing rates, and NPD (Koketsu and Dial, 1997).

In addition, other studies showed that feed limitation during a lactation period before weaning tended to have a negative effect on subsequent reproductive performance in breeding sows due to body condition loss (Xue et al., 1993; Tantasuparuk, et al., 2001a). In the study of Koketsu et al. (1996), the effect of feed intake patterns during lactation on sow reproductive performance was found. In their study, lactating sows were fed three types of the feed intake patterns between 9.25 lbs or lower and 12.5 lbs. They suggested that a high level of feed intake (greater than 9.25 lbs daily) was appropriate for sows with extremely short lactation length.

Moreover, Thaker and Bilkei (2005) examined the effect of lactation weight loss on subsequent reproduction of sows. They found that increased weight loss of sow during lactation resulted in decreased subsequent reproductive performance (farrowing rate, WSI, and total pigs born). Lactation weight loss increased 5 to 10 % in parity 1 sows, resulting in increased WSI (P < 0.05) and decreased pigs born alive (P < 0.001). Furthermore, lactation weight loss above 10% impacted subsequent farrowing rate in all parities. Tantasuparuk et al. (2001a) in agreement supported that body weight loss during lactation could particularly impact the length of WSI in parity 1 and 2 sows. This could indicate that lactation feeding
strategies were very important in order to improve reproductive performance of young parity sows.

**Factors affecting litters per sow per year**

**Genetic type**

Variation in reproductive performance of the sow has both genetic and environment components. Within genetic line, reproductive performance of crossbred sows has some advantages above that of purebred sows due to heterosis of crossbreeding (Falconer and Mackay, 1996; Bourdon, 2000). Literature supports the heterosis advantage studied by Cassady et al. (2002). Crossbred females were younger reaching puberty, heavier at farrowing, and more prolific and heavier in litter size than purebred females. Tantasuparuk et al. (2001b) examined the influences of breed differences on WSI in first parity and longevity of 2,365 purebred and 9,334 crossbred sows. They found that purebred sows had a longer average WSI than crossbred sows. Crossbred sows with first WSI within 5 days had the highest total piglet born. Moreover, differences between purebred sows existed. Tummaruk et al. (2000a) studied reproductive performance of Swedish Landrace and Yorkshire. They reported that Landrace sows had a greater reproductive performance than Yorkshire sows. It appears that Landrace sows had a higher farrowing rate (P < 0.05), longer WSI (P < 0.001), and more pigs born alive (P < 0.001) than the Yorkshire sows.

**Parity**

The effects of parity on herd productivity have been long understood. It has been documented that poorer reproductive performance in a breeding female is found in younger parities, reproductive performance rises as parity increases up to mid parities (3 to 6), and performance tends to decline in older parities (Hurtgen and Leman, 1980; Clark et al., 1989;
Correa et al., 2002). A similar finding of Koketsu et al. (1997b) and Tummaruk et al. (2000a) indicated that the highest repeat service rate and lowest farrowing rate were found in parities 1 and 2, and the highest proportion of not-in-pig sows was found in parities 9 and 10 sows. Moreover, the repeat service rate decreased in parity 2 sows and remained steady.

In the study of Koketsu (2005b), 148 commercial farms using PigCHAMP database in North America was examined. They examined a pattern in parity proportions with herd productivity, and compared the productivity of the changes in parity proportion between a herd which maintained a stable parity and a herd which had a fluctuating parity over 2 years. The reproductive productivity was found to be greater in a herd which maintained a stable parity pattern than that of fluctuating parity pattern. It appears that a herd, which maintained a high proportion of mid parity sows (Parity 3 to 5) in a year, was correlated with greater farrowing rate, LSY, PWSY, and shorter NPD (P < 0.01).

**Season**

High ambient temperature is considered a critical environmental factor affecting sow fertility in a breeding herd. High temperature can cause increased heat stress in animals, and the stress can negatively affect the activation of ovarian function via the hypothalamic-pituitary-ovarian axis in sows and spermatogenesis in boars (Love et al., 1995; Peltoniemi et al., 1999). Several studies have shown the adverse effect of the high temperature on poor reproductive performance in breeding sows such as a prolonged WSI, reduced embryonic survival, and decreased subsequent farrowing rate (Clark et al., 1989; Love et al., 1993; Koketsu et al., 1997a; Hughes, 1998; Peltoniemi et al., 1999; Tantasuparuk et al., 2000; Tummaruk et al., 2000b).
Previous studies reported that a high ambient temperature, especially during summer and early fall months increased reproductive failure in breeding females (Koketsu et al., 1996; Gourdine et al., 2006). Koketsu et al. (1997a) investigated the risk factors associated with types of reproductive failure of 11,705 sows from 30 herds in the United States. A high proportion of regular and irregular return to service was found in sows farrowing during summer and spring seasons. In addition, sows farrowing in the summer months had longer WSI than other months. In Sweden, Tummaruk et al. (2000a) reported that sows which were bred in August had the lowest farrowing rate and the highest repeat service rate.

In a tropical country, a study investigated the effects of season, temperature, and humidity on the reproductive performance of 11 herds in Thailand (Suriyasomboon et al., 2006). Sows weaned from May through October had prolonged WSI. Moreover, July and August were the months of the highest re-mating rate, whereas November to February were the months of the lowest re-mating rate. Similarly, Gourdine et al. (2006) examined the negative effects of the hot season on performance of lactating sows raised in a humid tropical climate. They found the negative effect of the hot season on feed consumption during the lactating period. The sows reduced their feed consumption during the periods of the hot days between 10 am and 15 pm. Furthermore, studies reported the impact of season on parity. Primiparous sows were more sensitive to high temperature periods than multiparous sows. As a result of varied temperature in a year, primiparous sows weaned during June through October had a significantly longer WSI (P > 0.05) than multiparous sows, which weaned during January through May (Hurtgen et al., 1980; Tummarak et al., 2000a).

In order to reduce the impact of high ambient temperature on herd fertility, the use of cooling systems (evaporative drip, spray cooling, circulating fan, and evaporative cooling)
are suggested to reduce variations affecting reproductive performance in a herd (Love et al., 1993; Peltoniemi et al., 1999; Tummaruk et al., 2000b; Suriyasomboon et al., 2006). On the other hand, Hurtgen et al. (1980) reported that the use of cooling systems could cool down the hot temperature, but it would not prevent a prolonged weaning-to-estrus interval and repeating service rate.

**Genetic parameters for reproductive traits**

*Heritability*

Reproductive traits such as age at puberty, litter size, litter weaning weight and rebreeding interval are important to herd productivity and profitability (Rydhmer, 2000). In general, reproductive traits are known to have low heritability with a low percent of the variation in performance due to genetic effects (Bourdon, 2000). Although the heritabilities of reproductive traits are relatively low, the possibility to improve reproductive performance in a breeding herd can be effectively conducted by using the animal model method Best Linear Unbiased Prediction (BLUP) models for selection. Many studies have primarily focused on the selection for increased litter size, including the number of total pigs born, pigs born alive, and pigs weaned (Fahmy et al., 1979; Ten Napel et al., 1995; Tholen et al., 1996; Adamec and Johnson, 1997; Arango et al., 2005). Other studies have sought to reduce the interval between weaning and farrowing to improve number of litters per year (Hanenberg et al., 2001; Holm et al., 2005).

*Heritability for litter size*

Litter size is the most important reproductive trait which is generally included in a breeding program (Rydhmer, 2000). Previous literature reports have shown that heritability estimates for litter size were relatively low. Ehlers et al. (2005) examined the genetic
parameters for sow productivity traits from purebred and crossbred sows. They reported that the estimated heritabilities for number of pigs born alive (NBA) were 0.155 and 0.146 for purebreds and crossbreds, respectively. However, other studies found smaller heritability of NBA. For example, Serenius et al. (2004), Holm et al. (2004), and Arango et al. (2005) reported estimated heritabilities of NBA ranging from 0.07 to 0.10.

The heritabilities for number of pigs weaned were lower than those for number of total pig born and born alive (Chen et al., 2003; Arango et al., 2005). Similarly, Ademec and Johnson, 1997 reported that heritabilities for total pigs born, number born alive, and pigs weaned were 0.11, 0.10, and 0.08 respectively. The heritabilities of number of total pig born and pigs born alive slightly increased with parity number (Tholen et al., 1996). Hanenberg et al. (2001) estimated genetic parameters for litter size traits at different parities. Using multivariate analyses for the efficiency of litter selection, they reported that the heritabilities of total pigs born and pigs born alive slightly increased with increasing parity number, with the exception of parity 2.

**Heritability for rebreeding intervals**

The variation of intervals after weaning was considered to be mostly affected by management such as feed intake in lactation period, estrus expression, boar contact, insemination time, and estrus detection (Tholen et al., 1996; Peltoniemi et al., 1999; Langendijk et al., 2000; Knox et al., 2004). However, genetic variation also exists (Ten Napel et al., 1995; Ademec and Johnson, 1997; Holm et al., 2005). Previous studies estimated the genetic parameters of rebreeding intervals such as farrowing interval (FI), WEI, WSI, WCI to investigate the possibility of selection improvement in production.
Estimates of heritability for the intervals after weaning were relatively low, and ranged from 0 to 0.2. In an Australian study, Tholen et al. (1996) found that heritabilities of FI and WCI from first and second parity sows were fairly low and ranged from 0.08 to 0.10. Similar results were found by Adamec and Johnson (1997). They examined the genetic relationships among rebreeding intervals of 2,896 Yorkshire and Landrace sows in Czech. The heritability of FI and WCI was quite low at 0.07 and 0.06, respectively.

Parameter estimates for WEI and WSI were expected to be similar due to a small difference of periods between estrus expression and first insemination (Adamec and Johnson, 1997). In the American study of Ehlers et al. (2005), the heritabilities of WEI in a single herd were 0.205, 0.239 and 0.202 for purebred, crossbred and pooled data, respectively. In agreement, Fahmy et al. (1979) and Ten Napel et al. (1995) reported the larger heritability for WEI ranging from 0.224 to 0.435. The heritability estimates of WSI were found between 0 and 0.2 (Adamec and Johnson, 1997; Rydhmer, 2000). Hanenberg et al. (2001) reported that the heritability for WSI was higher in the first parity than older parity. Similarly, a Norwegian study by Holm et al. (2004) indicated that the heritability of weaning to first service interval of parity 1 and parity 2 Norwegian Landrace sows was 0.06 and 0.03, respectively.

Ten Napel et al. (1995) studied the selection for a short WEI after the first parity. Their study found that heritability of WEI after selection for the first parity sows was 0.17 compared to that of base population of 0.36. This study demonstrated that genetic selection for reducing WEI by decreasing a number of prolonged WEI would be essential to farrowing frequency due to increasing the number of sows expressing estrus in seven days. Similarly, a study of Hanenberg et al. (2001) and Holm et al. (2005) reported that selection for reduced
WSI after the first and second litters tended to reduce the probability of return. In addition, selection for decreasing intervals from weaning to conception and weaning to farrowing, as well as farrowing interval seemed to be ineffective due to low heritability (Tholen et al., 1996; Ademec and Johnson, 1997; Ten Napel and Johnson, 1997).

**Correlation**

There are a few studies for genetic correlations between litter size and the intervals after breeding. Previous studies found that the genetic correlation estimates between the intervals such as WEI, WSI, and WCI were close to zero or slightly negative. Ehlers et al. (2005) reported that the genetic correlation between NBA and WEI were low of -0.03 and 0.31 for purebreds and crossbreds, respectively. Genetic correlations of WSI and WCI with NBA were found between 0 and 0.08 by Ademec and Johnson (1997). Therefore, it appears that selection for improving the interval after weaning might not influence litter size due to lack of correlations among the traits.

**Relationship between herd economics and reproductive traits**

LSY is an important reproductive trait that can indicate the herd financial efficiency. Increasing LSY by improving its components such as rebreeding interval, farrowing rate, sow mortality rate, and NPD could possibly compensate the financial loss in a breeding herd (Koketsu, 2002; Bates, 2005). High NPD and intervals between a production event and removal could affect herd total costs, particularly feed cost and opportunity cost. An increase in total costs of between $67 and $71 per sow was expected if the average NPD increased from 30 to 45 empty days (Peet, 2004). Lucia et al. (2000a) evaluated reproductive and financial performance based on parity removal of breeding swine in the United States. According to their finding, lifetime gross profit per female increased as the average parity at
the time of removal increased. They reported that young breeding females (unmated gilts and parity 1 sows) were found in a high proportion of the removal because of reproductive failure. The increase in removed young females yielded higher NPD accumulation, daily cost, and replacement cost in the herd. Reducing culling of younger parities would possibly increase herd profitability.
CHAPTER 3. MATERIALS AND METHODS

Source herds for the data

Data from four herds (EC, BOX, SSS, and SYC) in the Midwest of the United States and one herd in the middle part of Thailand (GGP) were used in this study. Each herd used PigCHAMP® (version 4.10, University of Minnesota) sow management software to enter and maintain their sow records. The EC herd was composed of primarily Yorkshire purebred sows bred to produce either replacement Yorkshire females, or F1 Landrace-Yorkshire females for use in the BOX and SYC herds. The SSS herd was a closed herd genetic system which used purebred Yorkshire females to produce F1 and three-way cross replacement females for internal usage. The GGP herd was comprised of purebred Yorkshire and Landrace sows mated to produce purebred replacement females and F1 replacement females for internal usage and at times for sale to other herds not included in this analysis.

All of the breeding females were kept in individual stalls in confinement buildings. In the United States, sow diets were based on standard corn and soybean meal formulations, while the diets were based on broken rice and soybean meal in Thailand. During gestation, sows were limit fed daily an industry standard gestation diet. During lactation feed intake was restricted at farrowing and increased gradually over the first week of lactation. From day 8 of lactation until weaning, sows were fed ad libitum access to lactation diet.

Average lactation length was between 16 and 18 days in the United States and 20 to 22 days in Thailand. After day 2 post-weaning, detection of oestrus was performed twice a day (morning and evening) by mature boar contact and back-pressure stimulation. The date of standing oestrus was recorded and the details of each insemination were recorded. Sows were bred via artificial insemination, a target of twice for each sow. First service was done
within 8 to 12 hours after sows were found in standing heat and second service was done within 24 hours after the first service. The litter records of the purebred and crossbred animals were used to study the traits in question.

**Data description**

Reproductive data were extracted from PigCHAMP® (version 4.10, University of Minnesota) for analysis in this research. The data extracted from these herds (prior to data edits) included 50,649 litter records from 15,625 sows over the time frame ending in March 2007. Each litter of each sow was included in the analysis, and the information from each litter included the sow identification, parity, farrowing date of the litter (with year-month used as a contemporary group effect), number born alive, litter weaning weight and the weaning to first service interval. Information on each sow that went across litters included the sow identification, sire, dam, her genetics, number of litters farrowed per female per year (LSY), and pigs weaned per sow per year (PWSY). The major traits of interest for this study were the number of LSY and PWSY.

The LSY was the number of litters farrowed per year for sows which have a litter in their lifetime. This LSY was influenced by traits of the sow such as non-productive days (NPD), lactation length, and gestation length. In this study, the LSY was calculated by the sum of the gestation days divided by the sum of breeding female days in the same period, then reported on an annualized basis (PigCHAMP, 1996; NPB, 2002). After entry, a female was defined as a ‘breeding female’ until the date of her first service. After the first service, the female was referred to as a ‘mated breeding female’ (NPB, 2002). Breeding female days accumulated from the beginning at the first date of the animals’ entry into the breeding herd. Mated breeding female days accumulated from the date of her first service. A gestation day
was defined as a day in which a breeding female is gestated a litter that farrowed, accumulating the days between mating and farrowing, where the day of mating counted as day 0. LSY then was defined as the sum of gestation days in a period divided by the sum of breeding female days in the period, then annualized by multiplying by the factor (365/115) (NPB, 2002).

The PWSY was used as a measure of overall reproductive efficiency in a herd, to include both LSY as well as number of pigs weaned per litter. PigCHAMP® calculated PWSY as LSY * number of pigs weaned per litter (PigCHAMP, 1996).

**Data edits**

As a result of the crossbred sows from BOX and SYC and the purebred sows in EC sharing the same parents from the EC herd, the sows from these three herds were pooled as the EC-BOX-SYC herd group in this study. The SSS and GGP herd data were analyzed separately since they were both separate closed herd genetic systems using internal multiplication.

Any records of sows with missing values for their sire were removed from all analyses. Records of LSY and PWSY that had incomplete information were identified as missing values. Records from only the sows’ last parity were considered for analyzing of LSY and PWSY. Records for PWSY were recorded only on sows that had been removed from the herd, due to a condition in the data extraction process of PigCHAMP®. Furthermore, records from parity number 7 and above were pooled in the analysis. Contemporary groups were defined as year-month of farrowing within a herd. Genetics of the sows were classified into four groups (purebred Landrace, purebred Yorkshire, Landrace sired crossbred, and Yorkshire sired crossbred). The edited data contained observations from
11,283 sows (4,158 purebred and 7,125 crossbred sows). Table 2 shows the numbers of litters and sow records, sires of the sows, dams of the sows, contemporary groups, and means, and standard deviations for LSY and PWSY across herd groups. Table 3 shows descriptive statistics and number of sow records for each genetic group, where GGP was all purebreds, EC-BOX-SYC was both purebreds and crossbreds, and SSS was only purebred Yorkshire and crossbreds.

**Statistical analysis**

Data were analyzed using the SAS Version 9.1 (SAS, 2004). Descriptive statistics were derived using the MEANS and FREQ procedures to obtain the number records of sow, sire, dam, contemporary group, breed type, the means and standard deviations for the traits of three herd groups in Tables 2 and 3. The generalized linear model (GLM) procedure was used to analyze the significance of possible fixed effects of the dependent variables, where the significance levels were considered at P <0.05 and P <0.01. Then, least square means (LS-means) and standard errors (SE) of LSY and PWSY were estimated to measure the effects of sow parity (parity 1 to parity ≥6), contemporary group of farrowing, and genetic type (purebreds and crossbreds).

The UNIVARIATE procedure was used to test normality of data and their residuals with the normality assumption. There were two ways of testing normality in this study. One method was graphical (histogram) and another was numerical (skewness-kurtosis tests and Anderson-Darling/Cramer-von Mises test). Since the raw data of the traits had a left skewed distribution, and the normal assumption was rejected, data adjustment was necessary to obtain a more symmetrical distribution. This was done with adjustment for parity.
Model for the tests of fixed effects

The tests of significance for all fixed effects on the traits LSY and PWSY were obtained using the generalized linear model (GLM) procedure of SAS for both the purebred and crossbred data. The model for statistical analysis was as follows:

\[ Y_{ijkl} = \mu + \text{parity}_i + \text{breed}_j + \text{cg}_k + e_{ijkl} \]

Where

- \( \text{parity}_i \) = the fixed effect because of \( i^{th} \) parity
- \( \text{breed}_j \) = the fixed effect because of \( j^{th} \) breed type
- \( \text{cg}_k \) = the fixed effect because of \( k^{th} \) contemporary group
- \( e_{ijkl} \) = the random effect due to error.

Model for estimation of genetic (co)variance components

Genetic (co)variance components and genetic parameters were estimated from multi-trait animal models, using the Restricted Maximum Likelihood (REML) methods of BLUPF90-PigPAK version 2.5 (Duangjinda et al., 2005). The following bivariate models were used for estimating variance and covariance components of LSY and PWSY along with the resulting heritabilities and genetic correlations:

\[ y = Xb + Za + e, \]

\[ \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} X_1 & 0 \\ 0 & X_2 \end{bmatrix} \begin{bmatrix} \beta_1 \\ \beta_2 \end{bmatrix} + \begin{bmatrix} Z_1 & 0 \\ 0 & Z_2 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{bmatrix}, \]

\[ \begin{bmatrix} a_i \\ e_i \end{bmatrix} = \begin{bmatrix} G \otimes A & 0 \\ 0 & R \otimes I \end{bmatrix}, \]

Where:

- \( y \) = vector of observations,
- \( b \) = vector of fixed effects (contemporary group, breed and parity),
- \( a \) = vector of random additive genetic effects of sows,
\[ e \quad = \quad \text{vector of residuals,} \]
\[ X \quad = \quad \text{incidence matrix related records to fixed effects,} \]
\[ Z \quad = \quad \text{incidence matrix related records to random additive genetic effects of sows,} \]
\[ A \quad = \quad \text{a genetic relationship matrix,} \]
\[ I \quad = \quad \text{an identity matrix,} \]
\[ G \quad = \quad \text{matrix of additive genetic (co)variance for the two traits,} \]
\[ R \quad = \quad \text{matrix of residual (co)variance for the two traits} \]
CHAPTER 4. RESULTS AND DISCUSSION

Reproductive performance

In swine production, PWSY and LSY are two of the primary factors measuring differences in herd performance. The higher performing herds almost always have higher LSY and PWSY due to the strong and positive correlation between both traits (Stein et al., 1990b; Xue et al., 1993; Koketsu, 2000a). In this study, Table 2 shows the means of LSY, ranging 2.22 to 2.30 litters per sow per year, and PWSY, ranging from 18.8 to 19.84 pigs. This was consistent with previous reports (King et al., 1998; Lucia et al., 2000b; Koketsu, 2002). Table 3 shows the mean and standard deviation of LSY and PWSY by genetic group. In these datasets, purebred sows had greater LSY and PWSY than crossbred sows. This difference was contrary to expectation that crossbred animals should express better reproductive performance than purebred animals. This difference may be due to management differences between herds. Table 4 shows the least square means (LS-means) and standard errors (SE) of LSY and PWSY, compared between three herd groups used in this study. There are small differences between LS means and raw means for LSY and PWSY. LS means are means adjusted for known sources of variation and should more precisely compare the reproductive performance among three herds.

Across the three herds used in this study, LS-means of LSY ranged 2.23 to 2.33 litters per sow per year, and that of PWSY ranged from 18.21 to 21.93 pigs. LS means of LSY and PWSY for crossbred sows were consistent with the previous findings (King et al., 1998; Lucia et al., 2000b). Although there was no report of the purebred performance found in Thailand for these traits, crossbred performance for LSY and pigs born alive per sow per year was similar to that reported by Kunavongkrit and Heard (2000). In this study, LSY and
PWSY were higher (P < 0.05) in the GGP herd (all purebred sows) than in the EC-BOX-SYC and SSS herds. This difference does not fit the expectation of crossbred sows performing better than purebred sows. However, several factors possibly contribute to this difference between herd groups, including genetic base, herd management differences (such as the recorded entry to first service interval), environment differences, and the EC-BOX-SYC herd group consisted of three herds instead of one herd. This variation between herd groups is to be expected due to the above factors. This difference does not interfere with the goal of this research, to examine LSY and PWSY for potential genetic improvement. These sources of variation are to be identified and accounted for in the genetic analysis.

**Estimates of fixed effects**

The levels of significance for the fixed effects of breed, parity, and contemporary group on LSY and PWSY are summarized in Table 5. All fixed effects included in the linear model were highly significant among both LSY and PWSY traits for all herd groups (P < 0.01). The effect of breed, parity, and contemporary group has not been reported for LSY and PWSY traits. However, Xue et al. (1992) and Tantaduparuk et al. (2000) reported a significant effect of parity, breed, and contemporary group on reproductive traits such as a number of born alive and farrowing rate (P < 0.05), which are component traits of LSY and PWSY.

Past research has shown parity to exert a significant influence on reproductive performance as reproductive traits increase with an increase in parity number and decline after parity ≥ 6. Clark et al. (1988), Hughes (1998), and Suriyasomboon et al. (2006) indicated that farrowing rate, number of total pigs born, and number of pigs born alive increased with parity number and later decreasing to parity 6-8. Parity 3-5 sows were the
most fertile and prolific (Koketsu, 1999). The effects of different parity on LSY and PWSY are compared within a herd in Tables 6 and 7, respectively.

In this study, the reproductive performance across parities within a herd was consistent with previous literature (Koketsu, 2000a; Tummarak et al., 2000a; Correa et al., 2002). The LSY for parity 1 females in GGP herd was noticeably larger than that of parity 1 females in EC-BOX-SYC and SSS herd groups. The probable cause of this was that the entry to first service interval in the GGP herd was 0 days, while the entry to first service interval was 19 days for the EC-BOX-SYC and 13 days for the SSS herd groups. The reason for the 0 day entry to first service interval at GGP was a management decision to enter females into inventory on the day of first service (since females were ear tagged at first service rather than entry into the gilt pool as in the other herds). This forcing of entry to first service interval to 0 days then mathematically inflates the LSY for the P1 females in the GGP herd, with smaller increases in LSY at later parities. The LSY of parity 2 and 3 females in GGP herd was also larger than that of parity 2 and 3 females in EC-BOX-SYC and SSS herds. In contrast, the LSY of parity 4 to 6 females of EC-BOX-SYC and SSS herds was larger than that of parity 4 to 6 females in GGP herd. In each herd group, LSY increased as parity increased. This result is to be expected since sow removal is generally for failure to farrow, thus sows that remained in the herd for more litters had greater LSY.

PWSY for parity 1 females in GGP was also larger than that of parity 1 females in other herd groups. This difference was possibly related to the estimation of LSY (a component of PWSY) for the GGP herd. Another finding was the difference of PWSY across sow parity among three herd groups. The PWSY of all parity sows in GGP herd was larger than that of all parity sows in EC-BOX-SYC and SSS herds, except that of parity 5 sows,
which showed no difference across three herds. The difference between the herd groups did
not support the expected advantage from crossbreeding due to the influence of heterosis,
where crossbred animals have the advantage of heterosis in reproductive performance over
purebred animals (Bourdon, 2000). The differences in culling criteria between the herds
could cause some of these differences because these PWSY are from sows that have been
removed from the herd. Other differences in herd management (farrowing to weaning) and
disease control may possibly be a cause.

Previous research reported the differences of reproductive performance between
Landrace and Yorkshire sows (Tantasuparuk et al., 2001b; Tummaruk et al., 2000a; Serenius
and Stalder, 2004). The effect of genetic type within a herd and across herds is shown in
Tables 8 and 9. Yorkshire sows had greater LSY and PWSY than Landrace sows in the
purebred GGP herd (P < 0.05). On the other hand, the LS-mean of LSY was higher for the
Landrace sows than Yorkshire sows in the EC-BOX-SYC herd group (P < 0.05).

In the SSS herd group, crossbred sows had a higher LSY and PWSY when compared
to the purebred Yorkshire sows. In contrast, purebred sows had greater LSY and PWSY than
crossbred sows within EC-BOX-SYC herd (P < 0.05). These performance differences
between purebred and crossbred sows within EC-BOX-SYC herd were not as expected as the
reproductive performance of crossbred sows was less than that of purebred sows (Cassady et
al., 2002). This difference is probably due to the superior management of the purebred EC
herd compared to the crossbred Box and SYC herds (based on average performance over
time).

The purpose in including these fixed effects (herd group, breed, and parity) in the
genetic analysis is to quantitate the differences in the datasets used in this project, and then
remove these non-genetic sources of variation to more accurately estimate the genetic effects on LSY and PWSY. The inclusion of herd groups with different genetic sources and environments, while resulting in some fixed effect differences that are contrary to past research, represent the scope of the industry to which these results must be applied.

**Test for normal distribution**

Examining the normality assumption of data and their residuals is critical before fitting a data analysis model in the process of statistical and genetic analysis. The normality of data can be checked by a combination of the shape of the distribution curve, and statistical tests (Bourdon, 2000; Guangbin, 2004). The first step in assessing normality is to examine the distribution in graphic form. Normally distributed traits typically display the form of a symmetric or bell-shaped curve. Figures 2 and 3 show the distribution of unadjusted and adjusted LSY and PWSY data for each of the three herd groups analyzed. Adjustment was for the parity of the female, as discussed previously.

The distributional forms of unadjusted LSY and PWSY data were broad and asymmetrical with their histograms slightly right skewed of the midpoint. These distributions imply that PWSY and LSY were approaching normality, but probably not normally distributed. Therefore, data adjustment for parity was conducted to make a more symmetrical distribution. Adjustment was made based on the results of the fixed effects analysis previously shown in Tables 6 and 7. After adjusting for parity, the distribution forms of LSY and PWSY were noticeably more normally distributed under the blue curve (see Figures 2 and 3). These figures comparing between adjusted and unadjusted data suggest that parity adjustment for LSY and PWSY in each three herd has made obvious improvement towards normality.
There are also more objective statistical tests of normality. The results of tests for normality of residuals for adjusted LSY and PWSY data are presented in Tables 10 and 11. The tests of normality, based on Cramer-von Mises and Anderson-Darling statistics is that the null hypothesis of normality is rejected when calculated p-values are less than the chosen significance level (P < 0.01). In this study, the p-values of LSY and PWSY for all herds were less than 0.01, except that of PWSY for GGP herd. These results suggest that the residuals for all traits were not normally distributed in three herd groups, except for PWSY at GGP herd.

Skewness and kurtosis, which are used for measuring the shape and distribution of traits, are also reported in Tables 10 and 11. If the values of skewness and kurtosis are close to zero, the traits may indicate a normal distribution (Guangbin, 2004). In this study, the skewness and kurtosis of LSY and PWSY residuals were low, and close to zero. These indicate that the distribution had some values in tails and were slightly dispersed from the center of the distribution. These skewness and kurtosis results imply that residuals of LSY and PWSY for all herds were approaching a normal distribution.

The distribution of the traits LSY and PWSY appear to be normal after adjustment for parity; however, the distribution of the residuals appears to be slightly outside the normal expectation. These results would suggest that these traits would be suitable for genetic analysis; however, examination of a larger dataset for these traits would be informative in assessing normality.

Estimates of (co)variance components and heritabilities

In order to make genetic progress in a trait, there must be adequate genetic control, as measured by the trait heritability. Therefore the estimation of (co)variance components and
genetic parameters is an essential step in making genetic improvement from selection. In pig improvement programs, accurate estimates of the genetic and phenotypic variances as well as heritabilities are important for the prediction of breeding value and the selection potential (Falconer and Mackay, 1996; Bourdon, 2000). Estimated variance components and heritabilities of LSY, compared among herd groups, from bivariate models are shown in Table 12.

The additive genetic and error variances for LSY were somewhat different between the three herds, perhaps due to differences in population sizes and genetic origins. EC-BOX-SYC herd had a slightly greater additive variance and error variance than GGP or SSS herds. The heritability estimates of LSY in the three herds ranged from 0.09 and 0.18, all in the lowly heritable category. The heritability from the EC-BOX-SYC herd group was greater than that from GGP or SSS herd groups. There was difficulty in finding previous studies which estimated the heritability of LSY, so no comparisons to previous work are reported. However, others have noted that the heritabilities of related reproductive traits to LSY, such as WEI, WSI, and FI were of a similar magnitude (Ten Napel et al., 1995; Tholen et al., 1996; Adamec and Johnson, 1997). Furthermore, selection to reduce WEI and WSI was found to be possible, despite low heritability (Ten Napel et al., 1995; Hanenberg et al., 2001). Therefore, genetic improvement by selection in LSY could be possible as well.

Table 13 shows the variance components and heritability estimates for PWSY. These results show that the GGP herd, which was a purebred herd group, had greater additive genetic and error variances than the other herd groups, which were combinations of purebred and crossbred sows. However, the heritability estimates for PWSY were similar, about twenty percent for all three herd groups. This difference between herd groups in genetic
variation could be explained by different herd selection programs and different genetic sampling. The herd with both purebred and crossbred sows in the same herd had the least variation. The herd group with both purebred and crossbred sows, but with three herds (which could influence the overall variation) was intermediate. The herd group that was only purebred, but was in an environment of greater heat stress, had the most variation. In addition, another reason for differences in genetic variation may be because of the population size and the proportion of sow records per sire within a herd (Ehlers et al., 2005). While no other studies have examined the heritability of PWSY, similar studies reported that heritabilities of litter size from purebred data were slightly lower, and ranged from 0.06 to 0.15 (Tholen et al., 1996; Adamec and Johnson, 1997; Ehlers et al., 2005; Holm et al., 2005). Chen et al. (2003) indicated that litter size could be improved by selection, despite a lowly heritable range. This suggests that genetic improvement by selection for PWSY may be possible as well.

**Genetic correlations between LSY and PWSY**

It is important that traits included in the selection program do not have undesirable genetic correlations with other economically important traits. When an undesirable genetic correlation exists between two important traits, improvement in one trait is negated by decreasing value in other important traits. It is preferable to have the traits be desirably correlated, or be independent. Estimates of covariance components between LSY and PWSY for each group are presented in Table 14. EC-BOX-SYC had greater additive covariance than GGP or SSS, whereas there was a similar error covariance among three herd groups. The resulting estimates of genetic and phenotypic correlation are presented in Table 15.

The estimates of genetic relationship between LSY and PWSY were found to be
moderate to strongly positive (from 0.45 to 0.70), and desirable across herd groups. This suggests that selection for genetic improvement in LSY will complement genetic improvement in PWSY. The genetic correlation in the GGP herd was slightly lower than that of EC-BOX-SYC and SSS herds. The reason for the strong, positive genetic correlation between LSY and PWSY is the mathematical relationship between the traits. LSY and PWSY are measurable data (PigCHAMP, 1996), especially in computerized sow management software programs. Another reason of difference in GGP herd could possibly be due to a large impact of environment in a tropical country, as explained by Suriyasomboon et al. (2006) and Tantasuparuk et al. (2000). The high temperature and humidity in Thailand had major effect on the reproductive performance in sows and boars which impacted the number of total number of pigs born, pigs born alive, average birth weight, farrowing rate, farrowing interval, and WSI (P < 0.001).

There are no comparisons to previous work reported. However, genetic correlations between LSY and PWSY were related with the study of Tholen et al. (1996); Serenius (2004); Holm et al. (2005). The estimated genetic correlation of lifetime prolificacy and sow longevity with litter size was moderately favorable. In this current study, the phenotypic correlation was similar across herds at a moderate level. However, the correlation between LSY and PWSY was lower than the previous literature, which ranged from 0.57 to 0.89 (Stein et al., 1990b; Koketsu, 2002).
CHAPTER 5. IMPLICATIONS

One goal of animal breeding in the swine industry is to make permanent genetic improvement in economically important reproductive traits, especially in the number of PWSY and LSY. The possibility to fit LSY and/or PWSY into the selection program and accomplish the breeding goal was examined step by step. First, LSY and PWSY were mathematically computable and farm measurable traits, where accuracy of data recording is essential. Second, the distribution of both traits was considered to be normally distributed. The shape of the normal curve, which indicates the variability of the traits, is important for the accurate estimation of genetic parameters. Third, estimated heritability of the traits across the herds was found to be greater than zero, with a value of LSY in the low heritability range and that of PWSY in the low to moderate heritability range. For lowly heritable traits, it is possible to make genetic progress by utilizing BLUP based selection. Fourth, genetic correlations between both traits were moderate to strong, and favorable, suggesting that selection for genetic improvement in LSY or PWSY should complement each other. Therefore, inclusion of LSY or PWSY in genetic improvement programs on farms with the capability to accurately measure these traits, and utilize BLUP based breeding value programs, appears to offer possible genetic and economic improvement.
CHAPTER 6. LITERATURE CITED


Mabry, J. W., M. S. Culbertson, and D. Reeves. 1996. Effects of lactation length on weaning to first service interval, first service farrowing rate, and subsequent litter size. Swine Health Prod. 4:185-188.


## Table 1. Summary of breeding herd productivity

<table>
<thead>
<tr>
<th>Author</th>
<th># Herds</th>
<th>Reproductive Variables&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>WSI</td>
<td>LL</td>
</tr>
<tr>
<td>Wilson et al. (1986)</td>
<td>30</td>
<td>n/a&lt;sup&gt;b&lt;/sup&gt;</td>
<td>37.6</td>
</tr>
<tr>
<td>Stein et al. (1990b)</td>
<td>54</td>
<td>8.3</td>
<td>25.1</td>
</tr>
<tr>
<td>Van Til et al. (1991)</td>
<td>17</td>
<td>n/a</td>
<td>33.6</td>
</tr>
<tr>
<td>King et al. (1998)</td>
<td>61</td>
<td>7.2</td>
<td>20.5</td>
</tr>
<tr>
<td>Koketsu (2000a)</td>
<td>615</td>
<td>8.7</td>
<td>18.5</td>
</tr>
<tr>
<td>Lucia et al. (2000b)</td>
<td>28</td>
<td>n/a</td>
<td>23.9</td>
</tr>
<tr>
<td>Koketsu (2002)</td>
<td>23</td>
<td>8.2</td>
<td>21.3</td>
</tr>
<tr>
<td>Koketsu (2005a)</td>
<td>124</td>
<td>n/a</td>
<td>21.8</td>
</tr>
</tbody>
</table>

<sup>a</sup> WSI = Weaning to service interval; LL = Lactation length; FR = Farrowing rate; NPD = Non productive sow days; LSY = Litters per sow per year; PWSY = Pigs weaned per sow per year.

<sup>b</sup> n/a = Not available.
Table 2. Descriptive statistics for numbers of records, sow, sire, dam, phenotypic means and standard deviation for litters farrowed per sow per year (LSY) and pigs weaned per sow per year (PWSY) by purebred and crossbred groups

<table>
<thead>
<tr>
<th>Items</th>
<th>Herd group</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Purebred</td>
<td>Purebred/Crossbred</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GGP</td>
<td>EC-BOX-SYC</td>
<td>SSS</td>
</tr>
<tr>
<td>No. of records (litters)</td>
<td>7,394</td>
<td>19,584</td>
<td>12,988</td>
</tr>
<tr>
<td>No. of sow (head)</td>
<td>1,925</td>
<td>6,619</td>
<td>2,739</td>
</tr>
<tr>
<td>No. of sires (head)</td>
<td>163</td>
<td>239</td>
<td>72</td>
</tr>
<tr>
<td>No. of dams (head)</td>
<td>729</td>
<td>1,714</td>
<td>848</td>
</tr>
<tr>
<td>Means</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSY</td>
<td>2.30</td>
<td>2.22</td>
<td>2.27</td>
</tr>
<tr>
<td>PWSY</td>
<td>19.84</td>
<td>18.80</td>
<td>19.25</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSY</td>
<td>0.32</td>
<td>0.43</td>
<td>0.39</td>
</tr>
<tr>
<td>PWSY</td>
<td>5.63</td>
<td>4.02</td>
<td>4.55</td>
</tr>
</tbody>
</table>
Table 3. Descriptive statistics for litters farrowed per sow per year (LSY) and pigs weaned per sow per year (PWSY) by breed type for three herds

<table>
<thead>
<tr>
<th>Breed group</th>
<th>Overall</th>
<th>LSY</th>
<th>Means ± SD</th>
<th>PWSY</th>
<th>Means ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>GGP</td>
<td>1,925</td>
<td>2.23±0.4</td>
<td>19.12±5.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EC-BOX-SYC</td>
<td>6,619</td>
<td>2.30±0.4</td>
<td>20.20±5.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSS</td>
<td>2,739</td>
<td>2.16±0.4</td>
<td>18.14±4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>11,283</td>
<td>2.27±0.4</td>
<td>19.27±4.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a L = purebred Landrace; Y = purebred Yorkshire; LX = crossbred Landrace; YX = crossbred Yorkshire.
b SD = standard deviations.
c n/a = Not available.
Table 4. Least square means (LS-means) and standard errors (SE) for litters farrowed per sow per year (LSY) and pigs weaned per sow per year (PWSY) by herd group

<table>
<thead>
<tr>
<th>Herd</th>
<th># Records</th>
<th>LSY</th>
<th># Records</th>
<th>PWSY</th>
</tr>
</thead>
<tbody>
<tr>
<td>GGP</td>
<td>1,925</td>
<td>2.33 ± 0.01&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1,925</td>
<td>21.93 ± 0.18&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>EC-BOX-SYC</td>
<td>6,619</td>
<td>2.28 ± 0.01&lt;sup&gt;b&lt;/sup&gt;</td>
<td>4,634</td>
<td>18.55 ± 0.12&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>SSS</td>
<td>2,739</td>
<td>2.23 ± 0.01&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1,909</td>
<td>18.21 ± 0.15&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>abc</sup> Within a column, LS-means ± standard error with different superscripts differ (P < 0.05).

Table 5. Levels of significance for factors included in the statistical model

<table>
<thead>
<tr>
<th>Fixed Effect</th>
<th>LSY&lt;sup&gt;a&lt;/sup&gt;</th>
<th>PWSY&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GGP</td>
<td>E-B-S</td>
</tr>
<tr>
<td>Breed</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>Parity</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>Contemporary group&lt;sup&gt;c&lt;/sup&gt;</td>
<td>**</td>
<td>**</td>
</tr>
</tbody>
</table>

<sup>a</sup> LSY = litters farrowed per sow per year.
<sup>b</sup> PWSY = pigs weaned per sow per year.
<sup>c</sup> Contemporary group = year and month of farrowing.

** = P < 0.01.
Table 6. Least square means (LS-means) and standard errors (SE) for litter farrowed per sow per year (LSY) in purebred and crossbred groups by parity

<table>
<thead>
<tr>
<th>Parity</th>
<th>GGP</th>
<th>EC-BOX-SYC</th>
<th>SSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.10 ± 0.02&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.05 ± 0.01&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.97 ± 0.02&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>2</td>
<td>2.25 ± 0.02&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.23 ± 0.01&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.14 ± 0.02&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>3</td>
<td>2.36 ± 0.02&lt;sup&gt;c&lt;/sup&gt;</td>
<td>2.33 ± 0.01&lt;sup&gt;c&lt;/sup&gt;</td>
<td>2.26 ± 0.02&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>4</td>
<td>2.28 ± 0.03&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.38 ± 0.01&lt;sup&gt;d&lt;/sup&gt;</td>
<td>2.31 ± 0.02&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>5</td>
<td>2.33 ± 0.08&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>2.44 ± 0.02&lt;sup&gt;e&lt;/sup&gt;</td>
<td>2.39 ± 0.02&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>≥6</td>
<td>2.35 ± 0.02&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>2.52 ± 0.01&lt;sup&gt;f&lt;/sup&gt;</td>
<td>2.44 ± 0.01&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a-f</sup> Within a column, LS-means ± SE with different superscripts differ (P < 0.05).

Table 7. Least square means (LS-means) and standard errors (SE) for pigs weaned per sow per year (PWSY) in purebred and crossbred groups by parity

<table>
<thead>
<tr>
<th>Parity</th>
<th>GGP</th>
<th>EC-BOX-SYC</th>
<th>SSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.78 ± 0.31&lt;sup&gt;a&lt;/sup&gt;</td>
<td>16.22 ± 0.16&lt;sup&gt;a&lt;/sup&gt;</td>
<td>16.08 ± 0.21&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>2</td>
<td>20.13 ± 0.31&lt;sup&gt;b&lt;/sup&gt;</td>
<td>17.42 ± 0.18&lt;sup&gt;b&lt;/sup&gt;</td>
<td>16.71 ± 0.25&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>3</td>
<td>22.12 ± 0.33&lt;sup&gt;c&lt;/sup&gt;</td>
<td>19.23 ± 0.21&lt;sup&gt;c&lt;/sup&gt;</td>
<td>18.43 ± 0.26&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>4</td>
<td>20.51 ± 0.34&lt;sup&gt;b&lt;/sup&gt;</td>
<td>20.01 ± 0.23&lt;sup&gt;d&lt;/sup&gt;</td>
<td>19.40 ± 0.25&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>5</td>
<td>19.14 ± 0.32&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>20.83 ± 0.27&lt;sup&gt;e&lt;/sup&gt;</td>
<td>20.53 ± 0.27&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>≥6</td>
<td>23.36 ± 0.28&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>22.00 ± 0.19&lt;sup&gt;f&lt;/sup&gt;</td>
<td>21.65 ± 0.18&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a-f</sup> Within a column, LS-means ± SE with different superscripts differ (P < 0.05).
Table 8. Least square means (LS-means) and standard errors (SE) for litters farrowed per sow per year (LSY) by breed across groups

<table>
<thead>
<tr>
<th>Breed</th>
<th>Herd Group</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GGP</td>
<td>EC-BOX-SYC</td>
<td>SSS</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>2.24 ± 0.03&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.51 ± 0.03&lt;sup&gt;a&lt;/sup&gt;</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>2.31 ± 0.03&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.35 ± 0.01&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.19 ± 0.02&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>LX</td>
<td>n/a&lt;sup&gt;f&lt;/sup&gt;</td>
<td>2.17 ± 0.01&lt;sup&gt;c&lt;/sup&gt;</td>
<td>2.28 ± 0.02&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>YX</td>
<td>n/a</td>
<td>2.27 ± 0.01&lt;sup&gt;d&lt;/sup&gt;</td>
<td>2.27 ± 0.01&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a-d</sup> Within a column, LS-means ± SE with different superscripts differ (P < 0.05)
<sup>e</sup> L = purebred Landrace; Y = purebred Yorkshire; LX = crossbred Landrace; YX = crossbred Yorkshire.
<sup>f</sup> n/a = Not available.

Table 9. Least square means (LS-means) and standard errors (SE) for pigs weaned per sow per year (PWSY) by breed across herd groups

<table>
<thead>
<tr>
<th>Breed</th>
<th>Herd Group</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GGP</td>
<td>EC-BOX-SYC</td>
<td>SSS</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>19.83 ± 0.48&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20.46 ± 0.42&lt;sup&gt;a&lt;/sup&gt;</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>21.51 ± 0.45&lt;sup&gt;b&lt;/sup&gt;</td>
<td>19.90 ± 0.14&lt;sup&gt;a&lt;/sup&gt;</td>
<td>18.25 ± 0.22&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>LX</td>
<td>n/a&lt;sup&gt;f&lt;/sup&gt;</td>
<td>17.66 ± 0.14&lt;sup&gt;b&lt;/sup&gt;</td>
<td>19.42 ± 0.23&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>YX</td>
<td>n/a</td>
<td>19.12 ± 0.17&lt;sup&gt;c&lt;/sup&gt;</td>
<td>18.73 ± 0.13&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a-d</sup> Within a column, LS-means ± SE with different superscripts differ (P < 0.05)
<sup>e</sup> L = purebred Landrace; Y = purebred Yorkshire; LX = crossbred Landrace; YX = crossbred Yorkshire.
<sup>f</sup> n/a = Not available.
Table 10. Normality tests for residual of litters farrowed per sow per year (LSY) by herd groups

<table>
<thead>
<tr>
<th>Herd Group</th>
<th>GGP</th>
<th>EC-BOX-SYC</th>
<th>SSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cramer-von Mises</td>
<td>3.63</td>
<td>3.92</td>
<td>3.14</td>
</tr>
<tr>
<td></td>
<td>(&lt;0.005)</td>
<td>(&lt;0.005)</td>
<td>(&lt;0.005)</td>
</tr>
<tr>
<td>Anderson-Darling</td>
<td>21.19</td>
<td>22.93</td>
<td>17.47</td>
</tr>
<tr>
<td></td>
<td>(&lt;0.005)</td>
<td>(&lt;0.005)</td>
<td>(&lt;0.005)</td>
</tr>
<tr>
<td>Skewness</td>
<td>-0.82</td>
<td>0.21</td>
<td>0.18</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>1.06</td>
<td>0.63</td>
<td>1.41</td>
</tr>
</tbody>
</table>

* The numbers in parenthesis are p-values for the test statistics above.

Table 11. Normality tests for residual of pigs weaned per sow per year (PWSY) by herd groups

<table>
<thead>
<tr>
<th>Herd Group</th>
<th>GGP</th>
<th>EC-BOX-SYC</th>
<th>SSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cramer-von Mises</td>
<td>0.05</td>
<td>0.36</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>(&gt;0.25)</td>
<td>(&lt;0.005)</td>
<td>(&lt;0.005)</td>
</tr>
<tr>
<td>Anderson-Darling</td>
<td>0.32</td>
<td>2.29</td>
<td>1.62</td>
</tr>
<tr>
<td></td>
<td>(&gt;0.25)</td>
<td>(&lt;0.005)</td>
<td>(&lt;0.005)</td>
</tr>
<tr>
<td>Skewness</td>
<td>-0.01</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>-0.06</td>
<td>0.31</td>
<td>0.58</td>
</tr>
</tbody>
</table>

* The numbers in parenthesis are p-values for the test statistics above.
Table 12. Estimates of variance components and heritabilities for litters farrowed per sow per year (LSY) by herd groups

<table>
<thead>
<tr>
<th>Herd group</th>
<th>Variance components$^a$</th>
<th>Heritability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma^2_a$</td>
<td>$\sigma^2_e$</td>
</tr>
<tr>
<td>GGP</td>
<td>0.01</td>
<td>0.12</td>
</tr>
<tr>
<td>EC-BOX-SYC</td>
<td>0.04</td>
<td>0.16</td>
</tr>
<tr>
<td>SSS</td>
<td>0.01</td>
<td>0.12</td>
</tr>
</tbody>
</table>

$^a$ $\sigma^2_a$ = additive genetic variance; $\sigma^2_e$ = residual variance; $\sigma^2_{total}$ = phenotypic variance.

Table 13. Estimates of variance components and heritabilities for pigs weaned per sow per year (PWSY) by herd groups

<table>
<thead>
<tr>
<th>Herd group</th>
<th>Variance components$^a$</th>
<th>Heritability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma^2_a$</td>
<td>$\sigma^2_e$</td>
</tr>
<tr>
<td>GGP</td>
<td>6.32</td>
<td>20.3</td>
</tr>
<tr>
<td>EC-BOX-SYC</td>
<td>4.41</td>
<td>14.4</td>
</tr>
<tr>
<td>SSS</td>
<td>2.37</td>
<td>10.5</td>
</tr>
</tbody>
</table>

$^a$ $\sigma^2_a$ = additive genetic variance; $\sigma^2_e$ = residual variance; $\sigma^2_{total}$ = phenotypic variance.
Table 14. Estimates of covariance components for litters farrowed per sow per year (LSY) and pigs weaned per sow per year (PWSY) by herd groups

<table>
<thead>
<tr>
<th>Covariance</th>
<th>GGP</th>
<th>EC-BOX-SYC</th>
<th>SSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{a1a2}$</td>
<td>0.12</td>
<td>0.27</td>
<td>0.12</td>
</tr>
<tr>
<td>$\sigma_{e1e2}$</td>
<td>0.76</td>
<td>0.57</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Subscripts are defined as follows: $a$ represents the direct genetic effect and $e$ denotes an error covariance. 1 and 2 refer to LSY and PWSY, respectively.

Table 15. Estimates of genetic and phenotypic correlation between litters farrowed per sow per year (LSY) and pigs weaned per sow per year (PWSY) by breed groups

<table>
<thead>
<tr>
<th>Parameter $^a$</th>
<th>GGP</th>
<th>EC-BOX-SYC</th>
<th>SSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{g12}$</td>
<td>0.45</td>
<td>0.69</td>
<td>0.72</td>
</tr>
<tr>
<td>$r_{p12}$</td>
<td>0.41</td>
<td>0.43</td>
<td>0.43</td>
</tr>
</tbody>
</table>

$^a$ $r_{g12} =$ Genetic correlation between LSY and PWSY; $r_{p12} =$ Phenotypic correlation between LSY and PWSY.
Figure 2. Data distribution of unadjusted and adjusted litters farrowed per sow per year (LSY) data

GGP Herd Group for LSY

EC-BOX-SYC herd group for LSY

SSS herd group for LSY
**Figure 3.** Data distribution of unadjusted and adjusted pigs weaned per sow per year (PWSY) data

**GGP herd group for PWSY**

![Histogram of GGP herd group for PWSY](image)

**EC-BOX-SYC herd group for PWSY**

![Histogram of EC-BOX-SYC herd group for PWSY](image)

**SSS Herd group for PWSY**

![Histogram of SSS Herd group for PWSY](image)
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