The management of the lightweight piglets from modern pig systems

By

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Abstract

The management of lightweight pigs that have resulted from increases in sow prolificacy are a major challenge for modern pig systems. The overall aim of this thesis was to develop intervention strategies that improve the performance of light piglets without penalising heavy piglets, with the pre- and immediate post-weaning period being the most critical windows for intervention.

In the first experiment (Chapter 2) creation of litter uniformity pre-weaning optimized the performance of piglets born lightweight, with long term benefits up to slaughter; heavy piglets on the other hand were penalized by this strategy. Despite heavy piglet efforts to compensate for insufficient milk intake by increasing creep feed intake, this was insufficient for achieving similar growths to heavy piglets kept in mixed litters. That being said, piglets born heavy ate high amounts of creep feed whereas piglets born light hardly consumed any creep feed.

In Chapter 3, it shown that irrespective of birth weight mid parity sows were identified as best foster sows. Their piglets were weaned heavy, whilst having eaten high amounts of creep feed. Second parity sows also weaned heavy piglets, but due to piglet low creep feed intake they were unable to maintain this weight advantage post-weaning. Despite the high creep feed intake of primiparous sow reared piglets, these piglets were weaned light and remained light post-weaning.

Lightweight piglets did not seem to benefit from an amino acid enriched post-weaning starter regime (Chapter 4). Although birth weight is still commonly used as indicator for identifying runt piglets, not all light piglets are destined to remain light. In fact, piglet shape at birth such as, length and head circumferences in relation to birth weight, seemed better predictors of post-natal growth.

Chapter 5 evaluated the effect of weaning age, weaning weight and an increased allowance of nursery diets on the performance of piglets through 5 months of age. The results suggested that an enhanced allowance of the nursery diets was beneficial, but that delayed weaning may yield long term benefits for piglets weaned lightweight.

The data from this thesis provide novel information and implications for the management of lightweight piglets. Some lightweight piglets are able to improve their post-natal performance and creating the optimal environment such as litter uniformity, rearing them by mid parity sows and weaning later will be beneficial to them.

Declaration

This thesis has been composed by myself and has not been submitted as part of any previous application for a degree. All sources of information have been specifically acknowledged by means of referencing.

Anne Maria Stevina Huting

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Publications and conference abstracts

Peer-reviewed publications

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Conference and abstracts

Huting A. M. S., I. Wellock, and I. Kyriazakis. 2016. Cross-fostering affects the performance of both small and heavy piglets throughout production. Proceedings for the 67th Annual meeting of the European Federation of Animal Science, 29 August – 2 September 2016, Belfast, United Kingdom, Theatre presentation.

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List of abbreviations

a*	Chromaticity coordinate a* (- green to + red)
AC	Abdominal circumferences
ADG	Average daily gain
adjusted a*	a* corrected for the control litters
adjusted H*ab	H* corrected for the control litters
AIAO	All-in-all-out system
AIC	Akaike information criteria
b*	Chromaticity coordinate b* (- blue to + yellow)
BiW:CC	Birth weight/ cranial circumferences
BMI	Body mass index
BW	Body weight
CC	Cranial circumferences
C_i	Teat consistency
CI	95% confidence interval
cm	Centimetre
CP	Crude protein
CRL	Crown rump length
CTRL	Control regime
CV	Coefficient of variation
d	Day
DDF	Denominator degrees-of-freedom
DE	Digestible Energy
FI	Feed intake
H*	Hue angle
HL	Snout to crown length
HL:BiW	Snout to crown length/ birth weight
IUGR	Intra uterine growth restriction
kg	Kilogram
LSM	Least square mean
m	Metre
MOF	Margin over feed
NE	Net Energy
ns	Not significant
OR	Odds ratio
PCA	Principal component analysis
PDIFF	Protected difference
PI	Ponderal index
R	Pearson correlation coefficient
scaled ADG	ADG scaled to body weight
SD	Standard deviation
SE	Standard error
SED	Standard errors of the differences of means
SGA	Small for gestational age
SMM	Studentized maximum modulus
true a*	a* corrected for the white tile

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Chapter 1.
General introduction

Batch utilisation efficiency, or the lack thereof, is a major challenge for pig producers, particularly in all-in-al-out (AIAO) systems and is challenged by the hyper prolific nature of the modern sow and the suboptimal conditions piglets are raised in. Batch inefficiency negatively influences barn utilization and may result in financial penalties at slaughter for delivering pigs that fall outside the body weight range of the slaughterhouse defined ideal (Brumm et al., 2002; Patience et al., 2004). In a true AIAO system, facilities should be emptied completely before the next batch of pigs arrive. Although, many pig producers aim to follow a AIAO system, this is often not the case. In fact, lightweight pigs are frequently held back from the normal production flow and in some cases mixed with similar sized pigs of the following batch (Calderón Díaz et al., 2017a). By doing this, pig producers expect to reduce economic losses by keeping slow growing pigs longer on the farm enabling them to reach slaughter weight within the appropriate range. However, they often do not realise that holding pigs back compromises biosecurity and increases production cost as it induces additional expenses for labour, feed, and barn utilisation. Moreover, this practice may result in slaughter penalties as a result of poor carcass grading as pigs accumulate excessive fat (Calderón Díaz et al., 2017a) especially when feeding them the same feed and applying the same management to slow growing pigs.

Modern pig systems face the challenge of lightweight pigs. Pigs can be lightweight at any stage of production (Douglas et al., 2013; Paredes et al., 2012), but the most critical period where most of the growth retardation occurs is during lactation and the weaner phase (López-Vergé et al., 2018).

1.1 Origins of lightweight pigs

1.1.1 *Variation at birth*

The number of piglets weaned per sow per year is an important economic trait and it has been suggested that it will most likely increase to around 30 to 40 in the coming decades (Koketsu et al., 2017). Selecting for prolificacy but not for sow uterine capacity (e.g. blood flow, space) however, has detrimental effects on birth weight, litter uniformity, and neonate viability (English 1969; Foxcroft et al., 2006; Matheson et al., 2018). Although increasing litter size increases uterine blood flow, this increase is not infinite and at a certain point it limits the uterine blood flow per foetus (Père and Etienne, 2000). Consequently, for every additional piglet average birth weight declines by 35-43 g, the number of piglets born lightweight increases (Quesnel et al., 2008; Beaulieu et al., 2010a) and litter variation increases (Boulot et al., 2008; Quesnel et al., 2008). However, overcrowding does not limit to decreasing birth weight and increasing the number of piglets born lightweight (Beaulieu et al., 2010a; Rutherford et al., 2013), but may also result in more piglets born with a higher brain weight to liver weight ratio, i.e. the "brain sparing effect" (Town et al., 2004; Foxcroft et al., 2006) a sign of intra uterine growth retardation (IUGR). The "brain sparing effect" is an adaptive response to placental insufficiencies and nutritional retardation in which the brain is spared at the expense of other organs. In essence this strategy aims to maintain oxygen supply to the brain as much as possible and to decrease the foetus's nutritional demand in situations where nutrient supply/ oxygen is limited, improving foetus's survivability (Wollman, 1998; Roza et al., 2008).

The problem of growth restricted piglets is known to exist for more than 3 decades with large deviations and extreme outliers present in 30-35% of the litters (Royston et al., 1982; van der Lende and de Jager, 1991). Under those circumstances (litter sizes of ~8 piglets/sow), one or more piglets was born extremely light in 30% of the litters, whereas extreme outliers to the right (heavy piglets) were hardly ever seen (~5%) (van der Lende and de Jager, 1991). This number will most likely increase in the hyper prolific sow, since the number of piglets with a birth weight lower than the 10^{th} centile are already more common in litter sizes of 7 and more (Bauer et al., 1998). Despite the different definitions in the literature with respect to what birth weight makes a piglet being born light, around 15% of the newly born piglets weigh less than 1.11 kg at birth (Feldpausch et al., 2016) and around 10-15% of the live born piglets (not only those born light) are born IUGR (Chevaux et al., 2010; Hansen et al., 2018; Matheson et al., 2018). These numbers increases with increasing litter size, with small pigs (< 1.00 kg) representing <10% of the population in litter sizes of ≤ 13 piglets, and 23% in litter sizes of > 15 piglets (Quiniou et al., 2002; Quesnel et al., 2008; Beaulieu et al., 2010a).

Although birth weight is an important factor for subsequent performance, the same studies also suggest that not all lightweight piglets are the same, as some are able to improve their growth in later life, whereas others remain permanently stunted (Paredes et al., 2012; Douglas et al., 2013; He et al., 2016). There are two types of lightweight piglets at birth, piglets born small (short) for gestational age (SGA) or piglets born IUGR (Rutherford et al., 2013). Human literature suggests that SGA infants may not be growth impaired, whereas IUGR are (Wollmann, 1998). In addition, the consequences of growth restriction are dependent on the duration and the stage of gestation growth restriction occurred (Wu et al., 2006). For instance, retardation during early gestation may result in symmetric growth restriction (i.e. proportionally small; around 80% of infants that are born lightweight) in which infants failed to reach their genetically growth potential, whereas asymmetric growth restriction (around 20% of lightweight infants) can happen during the latter part of pregnancy (Pollack and Divon, 1992; Dashe, 2000).

1.1.2 *Variation at weaning*

Weaning weight is crucial for subsequent performance (Mahan and Lepine, 1991; Larriestra et al., 2006; Douglas et al., 2013). The suboptimal circumstances that might impair piglets pre-weaning performance are numerous and include: insufficient colostrum intake, large litter sizes, body weight variation within litter, (repeated) cross-fostering, suboptimal teat position, impaired milking ability of the sow, and sickness (English, 1969; Thompson and Fraser, 1986; Douglas et al., 2013; Declerck et al., 2016a). These factors may not only affect piglets born lightweight but also piglets born heavier, as some piglets born lightweight are able to catch up growth during lactation (Douglas et al., 2013) and conversely piglets born heavy or normal weight may left behind in terms of growth

Variation in growth can occur at any stage of production with pigs that weigh considerably less than the average of the group are considered lightweight. But, before moving on to the identification of successful strategies to increase lightweight piglet performance, it is important to understand what makes piglets light at birth and/or weaning and to characterise their needs (i.e. what makes them different from their heavier counterparts).

1.2 Challenges of lightweight pigs

1.2.1 *Variation at birth*

The economic impact of growth retardation in pig production systems under normal farm conditions is difficult to predict due to differences between countries in for instance labour and feed costs, and pig prices. Nonetheless, from literature the consistent view is that especially lightweight piglets have a significantly lower pre-weaning survival rate (58 % vs. 92 % in heavy piglets) (Jourquin et al., 2016), need 7 to 14 days extra to reach slaughter weight (105 kg) compared with piglets weighing respectively 1.50 or 2.00 kg at birth (Quiniou et al., 2002), and have a poorer feed efficiency (Gondret et al., 2006). Schinckel et al. (2007) predicted that for piglets with a birth weight of 1 kg, a 0.1 kg increase in birth weight reduced the days to reach 105 kg by 2.86, implying that the extra days needed to reach slaughter weight can be even more resulting in additional feed costs and reduced barn utilisation as pigs are mostly sold on weight specifications rather than age.

The selection for leaner meat results in birth of piglets with limited body resources (Herpin et al., 1993; Le Dividich et al., 2005) and this together with the relatively higher surface-to-volume ratio (Amdi et al., 2013) for light compared with heavy piglets increases their energy requirement on a kg per pig basis (Noblet et al., 1987; Herpin et al., 2002). Furthermore, lightweight piglets have an impaired thermoregulation capacity (Caldara et al., 2014), whilst being born on a cold slatted or concrete floor in an environment that is comfortable for the sow (18-23 °C). Being at a competitive disadvantage for teat access compared with heavy piglets (De Passillé et al., 1988; Devillers et al., 2007) makes them extremely vulnerable to hypothermia and starvation (Herpin et al., 2002). Collectively these factors contribute to an increased latency time between birth and the first suckle (Herpin et al., 2002; Vasdal et al., 2011; Caldara et al., 2014), increased mortality (Vasdal et al., 2011) and decreased pre-weaning weight gain (Decaluwé et al., 2014). It is therefore not surprising that the majority of piglets that died from starvation were born light (Westin et al., 2015; Pandolfi et al., 2017). This may especially be the case for IUGR piglets, since growth retarded neonates are more susceptible to hyperthermia (Wu et al., 2006), are often found isolated from the other piglets and show low activity levels (Chevaux et al., 2010).

Furthermore, growth retardation is thought to have long term consequences for piglet postnatal physiology and metabolism (Roza et al., 2008). Various researchers have found that the relative length (cm/kg) of the small intestine was longer, but that its linear density (mg/cm) was lower (D'Inca et al., 2010; Wang et al., 2010; Alvarenga et al., 2013) with a shorter villus height and villus width (Wang et al., 2010) for IUGR compared with piglets born heavier. The small intestine does not only play an important role in the digestion and absorption of nutrients but also serves as a barrier against (feed-derived) pathogens. Thus any alterations may compromise piglets intestinal functioning, absorptive capacity, and gut barrier function (D'Inca et al., 2010; Everaert et al., 2017). Furthermore, some of these structural and functional difference of the intestinal epithelium still persist in IUGR piglets that survived the first few days post-partum (D'Inca et al., 2010) and even after 3 weeks post-partum (Wang et al., 2010). For instance, the alteration of various proteomes of the small intestine, liver and skeletal muscle, may result in an impaired development of the small intestine, liver and muscle (Wang et al., 2008; Wang et al., 2010). In addition, lightweight piglets gut bacterial community structure seem to differ during early-life (Li et al., 2018) compared with heavyweight piglets. Compared with heavyweight piglets lightweight piglets had a higher abundance of *Fusabacterium* and *Campylobacter*, which can be pathogenic, and a lower abundance of *Lactobacillus,* which are known to improve health and disease resistance. Lightweight piglets also had a lower abundance of butyrate-producing species such as *Faecalibacterium* and *Prevotella* an acetateproducing bacteria from which butyrate can be produced, important in improving intestinal barrier (Li et al., 2018). These differences make growth restricted piglets less efficient in nutrient utilisation (Wu et al., 2006), more susceptible to diseases (Wang et al., 2008) and mortality (Everaert et al., 2017) and may delay the development of the small intestine (Wang et al., 2010).

Also, differences in myogenesis (Foxcroft et al., 2006; Pardo et al., 2013) might result in a decreased protein synthesis and an increased fat deposition (Wang et al., 2008) of light piglets, thus poor carcass grading and inferior meat quality (Foxcroft et al., 2006; Pardo et al., 2013). A direct link between birth weight and the number of muscle fibres has been previously established (Gondret et al., 2006; Bérard et al., 2010). A low number of muscle fibres poses physiological limitations for performance inhibiting postnatal lean growth (Beaulieu et al., 2010a); skeletal muscle growth is more efficient than fat synthesis, therefore piglets with a greater number of muscle fibres at birth may grow faster (Alvarenga et al., 2013). However, the effect of birth weight on fat deposition seems to be more evident in females than males (Alvarenga et al., 2013) and plays a more prominent role during later life (> d 70) than during early life where birth weight has a stronger effect (Dwyer et al., 1994).

Given all these alterations, it is not surprising that piglets born lightweight have a lower gain, a lower gain to feed ratio and need longer to reach market weight (Wolter et al., 2002; Gondret et al., 2006; Beaulieu et al., 2010a). It should be noted that although that IUGR and SGA piglets should be considered as distinct populations within piglets that are born lightweight (Rutherford et al., 2013) the majority of studies looking at the effect of growth restriction on mortality, performance, gastrointestinal tract efficiency, and development etc., is still done on the basis of birth weight only.

Clinical characteristics of growth retardation (i.e. head morphology) that can be identified at any time after farrowing, are used to predict piglet viability (Hales et al., 2013; Matheson et al., 2018), but could also be utilized to identify piglets that remain stunted throughout life (Douglas et al., 2016). For instance, 1) differences in piglet shape at birth may direct towards to differences in the amount of maternal resources acquired during gestation important for development; and 2) piglets surface area: volume ratio (Amdi et al., 2013) which may influence piglets metabolic rate and thermoregulation. One of those measurements is ponderal index, which is birth weight divided by the cube of the height. The latter, identify infants whose soft tissue (e.g. muscle mass) is below average compared with their skeletal development (i.e. long and thin) (Pollack and Divon, 1993). Also abdominal circumferences, either as a proportion to head circumferences or not, is used to identify the proportion of soft tissue and may differentiate between infants that are born symmetric (i.e. proportionally small) or asymmetric (Dashe, 2000). Nonetheless, research on piglet morphometry at birth and postnatal performance is scarce and a whole system approach under commercial farm conditions is currently lacking (Douglas et al., 2016). The latter is imperative, as it may determine the success of pre- and post-weaning management strategies that are commonly used to help lightweight piglets thrive, especially since the growth potential of IUGR or "runts" might be forever compromised (Foxcroft et al., 2006). The current management approach of keeping SGA or IUGR piglets together or treating them the same may compromise their probability to catch up growth.

1.2.2 *Variation at weaning*

Piglets weaned light have a lower feed intake (Douglas et al., 2014a) and this together with their immature digestive system (Cranwell et al., 1997; Pluske et al., 2003) and higher epithelial cell turnover (Wiyaporn et al., 2013) compared with piglets weaned heavier, makes piglets weaned lightweight extremely vulnerable during the immediate post-weaning period. There can be multiple reasons to be weaned light, so that not only piglets born lightweight end up light at weaning (Paredes et al., 2012; Douglas et al., 2013). Although, piglets born heavier that ended up light at weaning may have suffered more severely from suboptimal conditions during lactation compared with piglets that were born and weaned light, they might still depended on the reason for being light be able to compensate growth post-weaning, whereas piglets born lightweight aren't (Wu et al, 2006). For instance, pigs that were fed restrictedly during nursery were able to compensate growth during the grower phase once pigs had access to diets that met their nutrient requirements (Kyriazakis et al., 1991; Douglas et al., 2014b). On the other hand, nutrient intake during lactation may "set" the appetite during later life (Hales and Barker, 2001).

1.3 What are the current strategies to enhance piglet performance during lactation?

Although the greatest body weight variation is seen at birth (López-Vergé et al., 2018), increasing birthweight or decreasing within litter variation is difficult to achieve. Therefore, management and nutritional strategies reducing body weight variation within batch by improving the performance of the light piglet rather than slowing down the growth of the heavier pig (Patience and Beaulieu, 2006; van Barneveld and Hewitt, 2016; López-Vergé et al., 2018) during the pre- and post-weaning periods will most likely be more effective.

1.3.1 *Maximizing colostrum intake*

There are multiple elements such as sow, piglet and environmental risk factors that contribute to pre-weaning mortality (Figure 1.1) (Edwards, 2002). One of them is insufficient colostrum intake. Piglets are born with limited body reserves that do not match their requirements for maintenance, thermoregulation, physical activity and growth (Le Dividich et al., 2005). Sufficient colostrum intake is therefore crucial for their survival and lifetime performance as it is rich in readily digestible nutrients and is an important supply of energy, maternal immunity and bioactive compounds essential for the development of the digestive tract (Devillers et al., 2011; Decaluwé et al., 2014; Declerck et al., 2016a). Unlike milk yield, colostrum production is independent of litter size: the larger the litter, the less colostrum is available per piglet (Quesnel, 2011; Decaluwé et al., 2014). Furthermore, the increase in litter size decreases the number of functional teats available per piglet thus increasing competition (Vasdal et al., 2011) and increases the time to the first suckle (Tuchscherer et al., 2000).

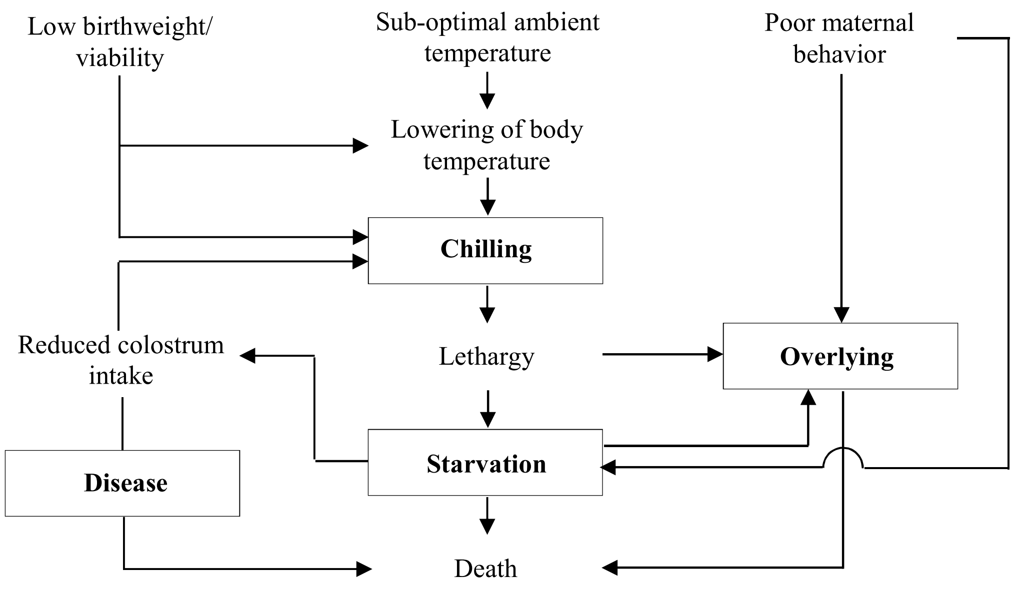


Figure 1.1 Factors affecting pre-weaning mortality (adapted from Edwards, 2002).

Although, piglets born lightweight require more energy on a kg per pig basis (Noblet et al., 1987; Herpin et al., 2002) and are extremely vulnerable to hypothermia and starvation (Herpin et al., 2002), they often acquire insufficient amounts of colostrum (Amdi et al., 2013; Ferrari et al., 2014; Declerck et al., 2016a). A lower colostrum intake in lightweight pigs may be a result of their impaired competiveness with heavier counterparts (De Passillé et al., 1988; Devillers et al., 2007) stemming from their reduced ability to reach the teat (Vanden Hole et al., 2018) and their reduced ability to actively massage and stimulate the teats (Baxter et al., 2008). These factors will all increase the latency time between birth and the first suckle (Herpin et al., 2002; Vasdal et al., 2011), which is positively associated with mortality (Vasdal et al., 2011) and negatively associated with pre-weaning weight gain (Decaluwé et al., 2014). Moreover, the smaller stomach size of lightweight piglets compared with piglets born heavier (Michiels et al., 2013; Huygelen et al., 2015) may suggest that lightweight piglet are physically unable to ingest enough colostrum.

Several studies have addressed routines that may stimulate colostrum intake (Kirkden et al., 2013). An indirect way that might promote colostrum uptake in lightweight piglets is by placing a neonate in a warm environment. Piglets experience a dramatic change in ambient temperature (~15-20 °C) once born (Baxter et al., 2008), while their lower critical temperature is around 34 °C (Vasdal et al., 2011). Preventing chilling will preserve limited endogenous fuels that the piglet can use in search and defence of a teat (Andersen et al., 2009) and may also be achieved by an oral supplementation of energy (i.e. energy boosters, colostrum) (Muns et al., 2015; Declerck et al., 2016b). Piglets that are able to maintain their optimal core temperature are more active and have a shorter latency time between birth and the first suckle (Vasdal et al., 2011). Hypothermia generally results in lethargy and given that lightweight piglets have a lower core temperature (Tuchscherer et al., 2000; Baxter et al., 2008) and a higher surface-to-volume ratio (Herpin et al., 2002), preventing chilling and providing an energy supplement or sow colostrum is suggested to be beneficial for reducing mortality (Andersen et al., 2009; Muns et al., 2015; Declerck et al., 2016b). Also assisted suckling, i.e. placing the piglet at the udder and making sure it sucked one of the teats, has been shown to reduce mortality (Andersen et al., 2007). Another direct way that may increase colostrum intake in large litters is split suckling, which consists of removing the heavier piglets that have already acquired sufficient amounts of colostrum from the litter for a maximum of 2 h while keeping them warm, may facilitate lighter piglet access to teats (Donovan and Dritz, 2000). Split sucking however, has only been shown effective in reducing litter CV at weaning rather than improving weaning weight (Donovan and Dritz, 2000). The aforementioned management techniques have mostly been effective in reducing pre-weaning mortality and may keep piglets alive that would otherwise die, therefore increasing competition within litter. In addition, they are often very laborious and complex thus not very practical in large commercial units where labour is expensive.

1.3.2 *Reducing competition within litter*

A sow can only nurse so many piglets as functional teats and rearing capacity are limited. Although selection for an increased number of teats is suggested to be possible (Rohrer and Nonneman, 2017), the number of functional teats has not increased as fast as litter size (Rutherford et al., 2013). In 2009 already 40% of the litters exceeded the number of mammary glands (Martineau and Badouard, 2009). As a result, cross fostering to even litter numbers is a common practice, although it may increase the risk of spreading diseases (Calderón Díaz et al., 2017b), especially in low health status farms (McCaw, 2000); may result in a higher incidence of lameness and abrasions on the carpal front knees due to fights to establish a fixed teat order (Sørensen et al., 2016); and may result in prolonged stress as shown in rats that were cross-fostered 5 days post-partum (Barbazanges et al., 1996). Re-arranging litters is generally practiced within the first 24-48 h postpartum (Heim et al., 2012) or at least within the first 4 days (van Erp-van der Kooij et al., 2003) to minimize aggression between the sow and her offspring and between piglets (Horrell and Bennett, 1981; Straw et al., 1998; Robert and Martineau, 2001). Although, repeated cross fostering, i.e. evening up numbers, correcting for dropouts, or moving individuals that are falling behind throughout lactation (> d 4), should be avoided as this may increase aggression between piglets resulting in teat disputes reducing weaning weight (Robert and Martineau, 2001; Reese and Straw, 2006), it frequently takes place (Calderón Díaz et al., 2017b). It has therefore been suggested that it is preferential to examine the cause of piglets that are falling behind (e.g. sickness, litter size not matching the milking ability of the sow, unproductive teats) and act on that, rather than eliminate the problem piglet(s) (Robert and Martineau, 2001).

The majority of Stakeholders (PIC, 2015; AHDB Pork, 2017a) recommend to keep small piglets together in order to prevent competition for the limited milk supply with heavier piglets. Creating litter uniformity is thought to be good for lightweight piglets, reducing competition for teat access (Mason et al., 2003) and assimilating the distribution of the limited resources. However there are some conflicting outcomes with respect to mortality and performance (Milligan et al., 2001; Deen and Bilkei, 2004; Douglas et al., 2014c) of lightweight piglets. For instance, some reported that creating litter uniformity improved survivability of piglets born light (Milligan et al., 2001; Deen and Bilkei, 2004) whereas others did not (Douglas et al., 2014c); similarly some reported a beneficial effect on performance (Deen and Bilkei, 2004; Douglas et al., 2014c) whereas others did not found such an affect (Milligan et al., 2001). Furthermore, research is lacking on the effects of creating litter uniformity on lifetime performance (i.e. to slaughter) and has not evaluated its effect on piglets born heavier.

1.3.3 *Utilizing sow milk potential*

One major component of promoting good pre-weaning performance is the milking ability of the sow. In commercial practice, producers have their own preference with regard to which foster parity is best for lightweight piglets. Primiparous sows often rear as many piglets as the number of teats they possess and it is important to ensure that all teats are suckled as this affects their performance in subsequent lactations (Farmer et al., 2012; 2017). As a result, some producers allocate lightweight piglets to primiparous sows, matching their low milk yield with the low requirements of lightweight piglets (AHDB Pork, 2017a). However, others use primiparous sows for heavier piglets to ensure that teats are sufficiently stimulated, without compromising sow body condition score which is important for reproduction (i.e. weaning to oestrus interval; Bierhals et al., 2012). In the latter case older sows with good teat quality are used for lightweight piglets. Similar discrepancies are also seen between advising bodies. AHDB Pork for instance advices to use young sows matching teat size with the mouth of the piglet (AHDB Pork, 2017a), whereas genus PIC advices producers to avoid using primiparous sows for piglets born lightweight (PIC, 2015) due to limitations in milking ability and their relatively "naïve" immune system (Cabrera et al., 2012; Quesnel et al., 2012; Carney-Hinkle et al., 2013). However, to maximize lightweight piglet pre-weaning and possibly post-weaning performance, it is imperative to understand which practice yields the best results.

Colostrum and milk yield depends on sow health and parity, being lower for primiparous sows compared with multiparous sows (Beyer et al., 2007; Hansen et al., 2012; Ngo et al., 2012). Studies evaluating the effect on foster parity have all concluded that primiparous sow reared piglets perform significantly less and are more susceptible to diseases compared with multiparous sow reared piglets (Bierhals et al., 2012; Miller et al., 2012; Carney-Hinkle et al., 2013). This might suggest that lightweight piglet growth potential is impaired when reared by primiparous sows. However, most of these studies focused on the average piglet (Bierhals et al., 2011), confounded parity treatments with birth weight (Miller et al., 2012; Carney-Hinkle et al., 2013; Craig et al., 2017), or in the case of focusing on lightweight piglets they maintained them in mixed litters (Ferrari et al., 2014), which in turn may have aggravated the effect of foster parity. On the other hand, teat quality may influence sow's suitability for lightweight piglets. Teat morphology changes with parity: as teat diameter and length increase with increasing parity (Balzani et al., 2016a; 2016b) and teats become harder to reach, thus increasing piglets latency time between birth and the first suckle (Vasdal and Andersen, 2012). This might be detrimental for lightweight piglets, due to their impaired rooting response (Baxter et al., 2008) and possibly weaker tongue strength as seen in infants (Vanden Hole et al., 2018).

1.3.4 *Additional resources to reduce variation*

The sow is often seen as the limiting factor (Zijlstra et al., 1996; Dunshea et al., 1999) for pre-weaning performance, with milk yield becoming insufficient to meet piglet nutrient requirements around 3 weeks of age (d 18) (Hansen et al., 2012) in spite of the fact that piglets in practice are often weaned at 4 weeks of age (European Commision, 2008). Thus an alternative approach is required to optimize pre- and consequently post-weaning performance when piglet's milk requirements outweigh sow milk supply.

Milk replacer. A milk replacer can be provided as a quick solution in case of depressed milk production either throughout lactation (Stewart et al., 2010; Douglas et al., 2014c), or during the last days prior to weaning (King et al., 1998; van Oostrum et al., 2016), especially during the summer months (Miller et al., 2012). Although there is some evidence that providing a milk replacer pre-weaning decreased mortality (Stewart et al., 2010), most studies conclude that milk supplementation increases weaning weight (King et al., 1998; Wolter et al., 2002; Miller et al., 2012; van Oostrum et al., 2016), whereas some did not find a positive effect (Stewart et al., 2010; Douglas et al., 2014c). However, Douglas et al., (2014c) focused on light piglets (<1.25 kg) that hardly consumed any milk replacer, whereas others focused on the average piglet (>1.30 kg). Milk replacer did not affect sow performance (i.e. body weight and back fat loss) (King et al., 1998; Wolter et al., 2002) suggesting that the increase in weaning weight resulted from increased intake. The increase in milk intake may promote the development of the digestive tract (Zijlstra et al., 1996), which may smoothen weaning and thus improve post-weaning performance. However, there is conflicting evidence about the effect of milk replacer on post-weaning performance with some studies recording positive effects (King et al., 1998; van Oostrum et al., 2016), while others did not (Wolter et al., 2002; Miller et al., 2012). These contradictory results might stem from differences in litter size (10 vs. 13 piglets/ sow) and weaning age (3 vs. 4 weeks) between the reported studies. Piglets dependency of other nutrient resources next to maternal milk, such as milk replacer, increases with increasing litter size and lactation length; milk yield usually reaches a plateau around 3 weeks of lactation whereas piglets requirements increases with increasing age (Hansen et al., 2012). The latter, will influence the amount of milk replacer consumed, which may increase weaning weight (and thus post-weaning performance) and may reduce the body weight variation within litter.

Creep feed provision. Weaning is accompanied by numerous stressors such as abrupt changes in litter composition (separation from the sow, co-mingling with other litters), diet (transition to solid feed) and environmental conditions resulting in a post-weaning growth check. The growth check in response to the acute transition to solid feed is characterized by anorexia, a rise in stomach pH, and impaired gut integrity (i.e. reducing villous height and increasing crypt depth), digestive capacity, and intestinal barrier function. The leaky gut syndrome and the increase in substrate in the large intestine available for the growth of pathogenic bacteria predisposes piglets to post-weaning diarrhoea (Campbell et al., 2013). These changes have both short- and long-term consequences on post-weaning performance and increase morbidity and mortality (Campbell et al., 2013). This might especially be the case for lightweight piglets since lightweight piglets are known to have a more immature digestive system (Cranwell et al., 1997; Pluske et al., 2003) and have a lower post-weaning feed intake than heavyweight pigs (Magowan et al., 2011a). The ban on the use of in-feed antibiotics and the reduction in zinc oxide (European Commision, 2003a; European Commision, 2016) makes weaning even a greater challenge. It is therefore not only important to wean piglets heavier, but also to habituate them to solid feed during lactation so as to ease the transition to solid feed post-weaning and increase post-weaning feed intake. Piglets that consume creep feed pre-weaning start eating sooner post-weaning (Bruininx et al., 2002; 2004; Carstensen et al., 2005), experience a greater weight gain (Kuller et al., 2007a; Collins et al., 2013) and have an increased net absorption in the small intestine, decreasing piglet susceptibility to post-weaning diarrhoea (Kuller et al., 2007b). However, creep feed intake varies considerably within and between litters (Carstensen et al., 2005; Collins et al., 2013). There are many factors that may stimulate piglets to consume creep feed such as litter size (Klindt, 2003), pre-weaning performance (Kuller et al., 2007a), teat position (Algers et al., 1990; Pluske et al., 2007), and weaning age (van der Meulen et al., 2010; Collins et al., 2013; Shea et al., 2013). However, studies (van den Brand et al., 2014; Middelkoop et al., 2018) investigating means to improve pre-weaning feed intake focused on the average piglet (van den Brand et al., 2014; Middelkoop et al., 2018). This is surprising, as in order to decrease within litter variation it is important to know whether lightweight piglets are able to compensate for possible insufficiencies in milk intake by consuming creep feed or whether lightweight piglets may lack the digestive maturity (Michiels et al., 2013) that might be necessary to effectively digest solid feed.

1.4 What are the current strategies to maximize performance post-weaning?

1.4.1 *Extending weaning age*

The various changes a piglet is exposed to at weaning and the consequences on post-weaning performance have been previously described. Especially piglets weaned light are extremely vulnerable post-weaning due to their lower feed intake (Douglas et al., 2014a) and their immature digestive system (Cranwell et al., 1997; Pluske et al., 2003).

With the current trends on the restrictions on the use of growth promoting antimicrobials and zinc oxide (European Commision, 2003a; European Commision, 2016), there is an increased requirement for alternatives which may reduce post-weaning growth check. One way to achieve this might be increasing weaning age. On the other hand, it has been suggested that milk yield insufficiency when weaned beyond 3 weeks of age may limit piglet lifetime performance (Collins et al., 2013). In Europe most piglets are weaned at 28 days of age (European Commision, 2008) and a potential further increase in weaning age beyond 4 weeks of age is expected to increase creep feed intake significantly (Callesen et al., 2007). This increase in creep feed consumption pre-weaning may improve the development of the gastrointestinal tract and thus reduces the growth check. Piglets weaned younger are thought to have a lower post-weaning feed intake (Dunshea et al., 2002; Leliveld et al., 2013), a less developed digestive system (Cranwell et al., 1997; Pluske et al., 2003) and consequently experience a greater post-weaning growth check (Colson et al., 2006) than piglets weaned older. However, most of these studies compared piglets weaned at 14 versus 21 days of age (Dunshea et al., 2002; Main et al., 2004), or 21 versus 28 days of age (Colson et al., 2006; Leliveld et al., 2013) and have neither focused on lightweight piglets nor did they draw comparisons at later weaning ages.

1.4.2 *Specialised feeding*

Furthermore, pigs born and or weaned light may benefit from specialised feeding, feeding the more complex diet(s) for a longer duration of time (Magowan et al., 2011b; Douglas et al., 2014a; Muns and Magowan, 2018) or feeding a high specification regime (Beaulieu et al., 2010b; Douglas et al., 2014a). Weaning is accompanied by a drop in feed intake (Lallès et al., 2007) and a reduced digestive and absorptive capacity (Owsley et al., 1986), However, the more developed digestive tract of pigs weaned heavy (Mahan and Lepine, 1991; Cranwell et al., 1997; Pluske et al., 2003) suggests that they are better able to cope with the diet transitions at weaning (Mahan and Lepine, 1991) than pigs weaned light. Feeding highly digestible and palatable diets with for instance, 1) fishmeal, which is rich in highly digestible amino acids (AA) and various macro and micro nutrients (Kim and Easter, 2001), 2) heat processed cereals, with reduced particle size and starch crystallinity which in turn increases digestibility and reduces the amount of substrate passing the large intestine (Medel et al., 2004; Wiseman, 2013), and 3) the lactose component of whey which increases feed intake and improves intestinal health (Mahan et al., 2004; Kim et al., 2010), may help lightweight piglets to compensate for their low feed intake.

1.5 Thesis aims

The aim of this thesis was to investigate management strategies that will reduce weight variability within pig systems. The strategies that were tested should enable lightweight piglets to decrease their growth deficit, either by increasing weaning weight or by improving post-weaning performance, without penalizing the performance of their heavier counterparts. The effectiveness of these strategies on the long-term were also evaluated.

The specific objectives of this thesis were:

- To determine whether sibling competition with heavier piglets influenced light- and heavyweight piglets pre-weaning performance in a similar way and whether the availability of creep feed enabled piglets to compensate for the lack of resources as a result of increased competition. This study also evaluated whether any of the differences seen at weaning persisted in the long term (Chapter 2).

- To determine whether foster sow parity influenced pre- and post-weaning performance of light- and heavyweight piglets that were kept in uniform litters and whether any deficiencies in milk intake during lactation were compensated by enhanced creep feed consumption (Chapter 3).

- To identify whether pre- and post-weaning compensatory growth for lightweight piglets, either born light and/or weaned light, is under the influence of birth weight or piglets shape. Furthermore, it investigated whether a nutrient enriched regime may enable lightweight piglets to compensate for the low feed intake post-weaning (Chapter 4).

- To determine whether weaning piglets at a later age, feeding a nursery feeding regime for a longer duration of time or the combination would improve post-weaning performance of lightweight piglets (Chapter 5).

Chapter 2.

What is good for small piglets might not be good for big piglets: the consequences of cross-fostering and creep feed provision on performance to slaughter.

2.1 Abstract

Major improvements in sow prolificacy have resulted in larger litters but, at the same time, increased the proportion of piglets born lightweight. Different management strategies aim to enhance the performance of, and limit lightweight piglet contribution to, body weight variation within a batch; however, consequences on heavyweight littermates are often neglected. This study investigated the effects of different litter compositions, created through cross-fostering, and the provision of creep feed on pre-weaning behaviour and short- and long-term performance of piglets born either lightweight (≤ 1.25 kg) or heavyweight (1.50–2.00 kg). Piglets were cross-fostered at birth to create litters with only similar-sized piglets (lightweight or heavyweight; UNIFORM litters) and litters with equal numbers of lightweight and heavyweight piglets (MIXED litters); half of the litters were offered creep feed and the remaining were not. Piglet behaviour during a suckling bout and at the creep feeder was assessed; a green dye was used to discern between consumers and non-consumers of creep feed. The interaction between litter composition × birth weight class influenced piglet body weight at weaning ($P < 0.001$): piglets born lightweight were lighter at weaning in MIXED litters than those in UNIFORM litters (6.93 vs. 7.37 kg); however, piglets born heavyweight performed considerably better in MIXED litters (8.93 vs. 7.96 kg). Total litter gain to weaning was not affected ($P = 0.565$) by litter composition. Teat position affected heavyweight piglet performance by d 10 ($P < 0.001$), with heavyweight piglets in UNIFORM litters being disadvantaged when suckling the middle and posterior teats. Creep feed provision did not affect body weight at weaning ($P > 0.05$) for either birth weight class. However, litter composition significantly affected daily creep feed consumption ($P = 0.046$) and faecal colour ($P = 0.022$), with heavyweight piglets in UNIFORM litters consuming the highest amount of creep feed and having the greenest faeces. In addition, a lower number of heavyweight piglets in UNIFORM litters were classified as non-consumers ($P = 0.002$). The weight advantage heavyweight and lightweight piglets had at weaning when reared in MIXED and UNIFORM litters, respectively, was sustained throughout the productive period. In conclusion, reducing body weight variation within litter (UNIFORM litters) was beneficial for piglets born lightweight but not for piglets

born heavyweight; the latter were disadvantaged up to slaughter. Although heavyweight piglets in UNIFORM litters consumed the greatest amount of creep feed, this was not able to overcome their growth disadvantage compared with heavyweight piglets in MIXED litters.

2.2 Introduction

The continuous improvement in sow prolificacy has increased litter size, whilst leading to a considerable decrease in average birth weight and an increase in the number of piglets born light (Beaulieu et al., 2010a; Rutherford et al., 2013). Light piglets, usually less than 1 kg at birth, are at a greater risk of dying pre-weaning (Hales et al., 2013; Ferrari et al., 2014), remain light throughout production (Beaulieu et al., 2010a; Paredes et al., 2012) and need more time to reach slaughter weight (Quiniou et al., 2002; Paredes et al., 2012); they thus, contribute significantly to batch inefficiency (Douglas et al., 2013). To reduce batch body weight variation, it is essential to develop strategies to improve the performance of light piglets.

Creation of uniform litters through cross-fostering reduces body weight variation within litter and lowers pre-weaning mortality of light piglets (Milligan et al., 2001; Deen and Bilkei, 2004), whilst weaned heavier (Deen and Bilkei, 2004; Douglas et al., 2014c). On the other hand, the effect of uniform litters on the performance of piglets born heavier is unknown, as they may face competition from similar sized pigs (Arnott and Elwood, 2009). Offering creep feed during lactation may reduce any potential negative effects on heavy piglets and maintain litter uniformity. It is notoriously difficult to predict the consequences of creep feed provision, which can be low and variable within and between litters (Bøe and Jensen, 1995; Bruininx et al., 2004; Collins et al., 2013). The objective of this study was to investigate the effect of litter composition and creep feed provision on the lifetime performance of piglets born light or heavy. It was hypothesized that piglets born light would benefit from being in litters with less weight variability, i.e. comprising of light pigs only. On the other hand, it was assumed that litter composition will not affect piglets born heavy; any potential adverse effects on them would be counterbalanced by creep feed provision.

2.3 Materials and methods

2.3.1 *Experimental design*

The experiment was a 2 x 2 x 2 factorial design; treatments involved birth weight class (light or heavy; to exaggerate the contrast for the effects of cross fostering), litter composition (UNIFORM or MIXED) and creep feed provision (yes or no). Piglets with a birth weight of ≤ 1.25 kg (minimum 600 g) were considered light, and piglets weighing between 1.5 and 2.0 kg were considered heavy, in accordance with the methodology of Douglas *et al.* (2013; 2014). The experiment was set up with a maximum of 6 litters per farrowing batch for practical reasons and in accordance to the farms capacity. To test the hypothesis for the effects of cross fostering on ‘non-light’ and light piglets, two extreme treatments of the light and heavy piglets were chosen to exaggerate the contrast. They were cross-fostered into litters of different compositions within 24 h from birth (see below). A power analysis was done using the PROC POWER statement in SAS version 9.4 (SAS inst. Inc. Cary, NC) to determine the required replicates based on the results of previous studies (Collins et al., 2013; Douglas et al., 2014). The experimental design was implemented on 37 sows and 442 piglets: 12 litters consisted of light only (UNIFORM L), 12 litters consisted of heavy only (UNIFORM H) and 13 litters consisted of both light and heavy piglets (MIXED light and MIXED heavy), with 6 light and 6 heavy piglets. Half of the UNIFORM and half of the MIXED litters were offered creep feed, whereas the other halves were not, resulting in at least 6 replicates per treatment. The litter was the experimental unit from birth to grower stage (~9 weeks of age). The experiment was conducted at Cockle Park Farm (Newcastle University, Morpeth, Northumberland, United Kingdom) and was approved by the Animal Welfare and Ethical Review Body (AWERB project ID no. 419) of Newcastle University. This project was sponsored by AHDB (Agriculture and Horticulture Development Board) Pork and Primary Diets.

2.3.2 *Animals, housing and management*

Multiparous sows farrowed on a 3 week cycle and were housed in conventional, partially slatted farrowing crates (237 x 194 cm). All sows were Large White x Landrace, inseminated with Hylean boar semen (Hermitage Seaborough, Ltd, Devon, UK). Sows were placed in crates on Monday and those that had not farrowed by Thursday were induced with a Prostaglandin analogue (Planate; Intervet UK, Walton, UK). The average number of piglets born alive was 12.1 (range 3 to 17) with an average birth weight of 1.47 kg (SD = 0.37), based on 121 sows that farrowed over the experimental period including experimental and non-experimental sows; the average litter size is consistent with the average seen in UK farms (i.e. 12.3 piglets born alive/litter), but lower from what is seen in other European herds (13.5 piglets born alive/litter; AHDB Pork, 2016). All sows were fed a home-milled meal twice a day and water was available *ad libitum* throughout lactation. The temperature in the farrowing unit was maintained at 21˚C (20.8˚C, range 17.3 to 25.4˚C).

During the first 2 days post-partum piglets were locked into the creep while the sow was eating, to minimize crushing. An infrared heat lamp (InterHeat; LPB300S 230v 50-60Hz, 250W) was located in the covered creep area and wood shavings were provided as bedding (Goodwills Wood Shavings, Ponteland, Newcastle Upon Tyne, UK). Piglets had unlimited access to a water nipple drinker, which was cleaned daily. Within the first 12 h after birth piglets had their teeth clipped. At ~3 days of age, piglets were tail docked and received an intramuscular iron injection (1 ml; Gleptosil, 200 mg iron/ml, CEVA Animal Health Ltd, Amersham, UK). At 7 days of age piglets were vaccinated against *Mycoplasma hyopneumoniae* (1 ml; M+PAC; Intervet UK, Walton, UK). The general health of piglets was examined on a daily basis in which piglet posture (i.e. hunched back), breathing (including coughing and sneezing), activity (e.g. mobility, lameness, responsiveness), and faecal consistency was assessed: any interventions were monitored and recorded. Medication administered for scour, swine dysentery and lameness were Norodine (Norodine 24, Norbrook, Corby, UK), Denagard (Novartis Animal Health, Grimsby, UK) and a 50:50 mixture of Pen & Strep (Pen & Strep, Norbrook, Corby, UK) and Tolfine (Tolfine, Vetoquinol, Paulerspury, Towcester, UK) respectively with the dose depending on the size of the pig. If more than 3 piglets in a litter were diagnosed with diarrhoea the whole litter was treated.

Piglets were weaned at approximately 28 days of age and vaccinated for *M. hyopneumoniae* (1 ml; M+PAC; Intervet UK, Walton, UK) and porcine circovirus type 2 (1 ml; Ingelvac Mycoflex; Boehringer Ingelheim, Ingelheim, Germany). Littermates remained together when moved to fully slatted nursery accommodation. Each pen (183 by 170 cm) had nipple drinkers and a multiple-space feeder allowing three piglets to feed simultaneously. All pigs had *ad libitum* access to a standard 3-stage pellet feeding regime (Primary Diets, ABAgri, Ripon, North Yorkshire, UK). Diet 1 was fed until 2 kg were consumed/ pig, diet 2 until 3 kg were consumed/ pig and was followed by the weaner feed which was fed *ad libitum* up to 9 weeks of age (grower stage) (Table 2.1). The initial room temperature in the nursery accommodation was set at 26˚C (26.1˚C, range 25.0 to 26.8˚C) and reduced by approximately 0.2˚C each day to a minimum of 22˚C (22.7˚C, range 19.9 to 23.5˚C).

When moved to the on-site grower accommodation, pigs were fed a home milled meal (20.4% CP, 9.83 MJ NE/ kg diet, and 1.17% total lysine). Upon moving to the grower building, pigs were pseudo-randomly mixed to give groups of 15-20 similarly sized pigs/ pen (320 x 210 cm). The pigs were kept in the same group up to slaughter. At approximately 12-13 weeks of age (~88 days) pigs were moved again to a fully slatted finisher building (pen size 500 x 304 cm) and were fed a commercial 'finisher' pelleted diet (16.1% CP, 9.69 MJ NE/ kg diet, and 1.00% total lysine). Pigs had *ad libitum* access to feed and water during the grower and finisher stages.

Table 2.1 Ingredient composition on an as-fed basis and chemical analysis of the creep feed and the post weaner feeds used.[1]

Ingredient, g/kg	Creep feed[2]	Post-weaning feeds		
		Diet 1	Diet 2	Weaner
Barley	128.7	75.0	75.0	150.0
Wheat	-	234.1	438.1	487.5
Micronized wheat	100.0	50.0	25.0	-
Micronized maize	-	25.0	-	-
Porridge oat	-	75.0	25.0	-
Oats	194.6	-	-	-
Wheat feed	-	-	12.5	25.0
Herring meal	100.0	75.0	60.0	25.0
Hi-pro soya meal	-	145.2	223.3	250.0
Full fat soya bean	-	25.0	25.0	-
Pig weaner vitamin/trace element supplement[3]	5.0	5.0	5.0	5.0
Dried skim milk powder	140.7	61.1	-	-
Whey	266.4	173.2	69.4	-
Potato protein	-	12.5	-	-
L-Lysine HCL	3.34	1.68	2.45	3.74
Dl-Methionine	2.27	1.45	1.31	1.56
L-Threonine	2.51	1.15	1.19	1.57
L-Tryptophan	0.85	0.22	0.01	0.18
L-Valine	0.72			
Vitamin E	0.15	0.41	0.21	0.10
Benzoic acid	-	5.00	5.00	5.00
Limestone flour	-	0.80	0.00	1.10
Dicalcium phosphate	-	0.00	5.10	8.90
Salt	-	0.00	1.15	4.10
Binder (LignoBond DD)[4]	-	0.00	0.00	6.25
Soya oil	54.6	33.2	25.2	25.0
Analyzed composition, % as fed				
CP	20.0	23.1	22.1	20.8
Crude fiber	1.8	2.0	2.4	3.2
Moisture	8.8	8.9	10.2	10.9
Ash	6.7	5.8	5.1	5.1
Calculated composition, % as fed or as specified[5]				
DE, MJ/kg	16.50	16.00	15.30	14.80
NE, MJ/kg	11.55	10.99	10.66	10.37
Calcium	0.75	0.59	0.54	0.59
Phosphorus	0.71	0.59	0.60	0.59
Lactose	25.00	15.00	5.00	0.00
Lys	1.60	1.60	1.50	1.40
SID[6] Lys	1.48	1.44	1.33	1.26
Met	0.67	0.60	0.54	0.50
SID Met	0.64	0.56	0.48	0.45
SID Thr	1.00	0.95	0.86	0.81
SID Trp	0.29	0.28	0.25	0.24

[1] Diets were supplied by Primary Diets, ABAgri, Ripon, North Yorkshire, United Kingdom

[2] Additional ingredient: 0.10 g/kg Chromic oxide

[3] It provided per kilogram of complete diet 11,500 IU of vitamin A, 2,000 IU of vitamin D_3, 100 IU of vitamin E, 4 mg of Vitamin K, 27.5 ug of vitamin B_{12}, 15 mg of pantothenic acid, 25 mg of nicotinic acid, 150 ug of biotin, 1.0 mg of folic acid, 160 mg of Cu ($CuSO_4$), 1.0 mg of iodine (KI, Ca $(IO_3)_2$), 150 mg of Fe ($FeSO_4$), 40 mg of Mn (MnO), 0.25 mg of Se (bone morphogenetic protein), and 110 mg Zn ($ZnSO_4$).

[4] Borregaard LignoTech, Sarpsborg, Norway

[5] Values estimated from the values in the Premier Atlas ingredients matrix (Hazzledine, 2008)

[6] SID = standardized ileal digestible

Pigs reached slaughter weight of 90 - 100 kg at approximately 165 days of age and were sent to slaughter in 2 groups/ batch irrespectively of treatment.

2.3.3 *Experimental procedures*

Piglets were weighed to the nearest 1 g within 12 h post-partum. Neonates that did not meet the birth weight criteria or those that had physical abnormalities (e.g. splay legs, anaemic) were cross-fostered onto non- experimental sows. Cross-fostering (d 0) was applied to create litters with 12 piglets per sow, including litters with only light or heavy piglets: MIXED litters consisted of equal numbers of light (n = 6) and heavy (n = 6) piglets. Piglets were pseudo-randomly allocated to one of the treatment groups, whilst balancing for sex and litter of origin. Only healthy multiparous sows (> 2 parity) with a sufficient number of functional teats were used to create experimental litters. Depending on the number of piglets available per batch, each litter composition was performed in duplicate. In order not to deprive piglets of access to colostrum from their biological mother, piglets were selected and individually identified by ear tagging and cross-fostered according to their birth weight class within 24 h after birth.

During the first 4 days post-partum all litters were given access to a commercial supplementary milk (Farmate, Volac, Royston, United Kingdom; protein 22%, fiber 0%, oil and fats 14%, ash 7.5% and lysine 2%) using a small metal bowl. The milk was refreshed daily by mixing 150 g milk powder with 1 L warm water. Piglets were trained by dipping their snout in the milk bowl twice a day during the first 2 days post-partum. During early lactation (< d 10), individual piglets were weighed daily; piglets that lost weight during 2 consecutive days were removed from the experimental litter and cross-fostered onto a non-experimental sow.

All piglets were weighed at 10 days of age. From then on and up to weaning, half of the litters were randomly assigned to having access to creep feed and the other half not. The creep feed (Primary Diets, ABAgri, Ripon, North Yorkshire, United Kingdom), provided as pellets, was supplemented with 1.0% chromic oxide as indigestible marker (approved by the United Kingdom Food Standards Agency). A feed hopper with two feeding spaces was fixed to the wooden board of the pen close to the creep area. To ensure that any spillage was accounted for, a wooden tray was attached to the hopper that partly covered the slats. The amount of creep feed offered and refused was measured on a daily basis and was checked throughout the day to ensure *ad libitum* creep feed consumption.

2.3.4 *Behavioural observations*

Teat pair and teat consistency. Piglet position at the udder during at least two successful suckling bouts was assessed on d 2, 5, and 10 of lactation. Position at the udder was classified according to teat pair locations 1-7, from anterior to posterior. The start of a successful sucking bout was defined when more than half of the piglets gathered at sow udder and began massaging. A sucking bout was considered complete when more than half of the litter had ceased massaging, either by physically leaving the udder, falling asleep at the udder or when the sow changed position (Douglas et al., 2014c). The position of each individual piglet and whether piglets used more than one teat during a milk let down was recorded. If a piglet visited more than one teat pair with the same intensity per observation day, the teat numbers were averaged. Piglet teat pair on d 2, 5, and 10 was used to determine teat fidelity. A piglet was given a consistency score (C_i) of 1 when it used the same teat pair during the suckling bouts assessed throughout the day (d 2, 5, and 10). The number of piglets that scored 1 within a litter was expressed relative to the total number of piglets in the litter. A fixed teat position has been established by d 10 of age (Skok and Škorjanc, 2014), therefore, suckling position at d 10 was used to analyse its effect on subsequent performance. The preferred teat pair was grouped classifying the first two teat rows as anterior, teat pair 3-5 as middle, and teat pair ≥ 6 as posterior (Kim et al., 2000).

Feeding behaviour. Time spend at the creep feeder by individual piglets was monitored using video-recordings on d 19, 21, and 25, as creep feed intake intensifies during the last week of lactation (Barnett et al., 1989; Bruininx et al., 2002); this was also confirmed by preliminary observations. Individual piglets were marked with a dark spray marker applying different combinations of marks. At approximately 0900 h cameras were turned on and left on for a period of 24 h. From 1600 h artificial lights in the farrowing house were switched off. During a 7-h period from 0900 h to 1600 h continuous records were taken using CowLog (CowLog 2.0 desktop, Hänninen and Pastell, (2009)). The total time (s) a piglet spent at the feeder was expressed relative to the time recorded. A successful feeding bout, was defined from the point the piglet placed its snout in the feeder/tray for more than 5 s. A feeding bout was considered to end when the piglet removed its head for at least 15 s (adapted from Pajor et al. 1991). As piglets spilled creep feed on the tray, behaviours directed towards the tray (i.e. piglet placing its snout in the tray, piglet removing its head from the tray) were also assessed.

2.3.5 *Individual creep feed intake*

In addition to the behavioural observation, the presence of the indigestible marker (chromic oxide) in the faeces was used for the assessment of individual creep feed intake. Faecal samples were obtained at 3 day intervals during the first 1 ½ weeks of creep feed provision (d 13, 16, and 19) and 2 day intervals during the last week before weaning (d 21, 23, 25, and 27). For collecting purposes, piglets were placed on a weighing scale for a maximum of 4 minutes, stimulating voluntary defecation; faecal consistency was recorded and samples with watery faeces were excluded from subsequent analysis. Both piglets of creep fed and non-creep fed litters were sampled and, in total, faecal material was obtained from 87% of them. Data collected on d 27 was not used as some litters were weaned prior to this.

The presence of the inert dye in the faecal samples was used in two ways to classify creep feed consumers and non-consumers through 1) the conventional subjective observation of visually green faeces (Bruininx et al., 2004; Collins et al., 2013); and 2) a new methodology via the colour reader (Color reader CR-10, Konica Minolta Sensing Inc., Sunderland, United Kingdom), measuring faecal appearance objectively.

Classification of consumers. Total creep feed intake increased significantly from d 19 onwards, therefore piglets showing visibly green faeces (dye present) at 19 days of age, were considered early consumers. In addition, piglets were defined as consumers according to the number of faecal samples that appeared to be visually green. They were grouped in different consumer classes (i.e. low, moderate, and high), following, the methodology of Bruininx et al. (2004) and Collins et al. (2013): piglets having visually green faeces on three occasions (d 19, 21, and 25) were classified 'high consumers'. Piglets which scored positive on two out of three sampling moments were classed 'moderate consumers'. 'Low consumers' were piglets having green faeces on one occasion, and 'non-consumers' never showed green faeces.

Colorimetric assessment of piglet faeces. The colour space used was CIELAB (Konica Minolta, 2007) resulting in numerical colour data: L*, a*, and b*. Measurements of interest were the chromaticity coordinate a*, which when negative indicates greener faeces, and Hue angle (H*), which defines how a colour is perceived. Angles can be calculated from a* and b* from which 0° represented red, 90° yellow, 180° green, and 270° blue: numbers in-between represent intermediate hues. Negative values of b* indicate colours towards blue and positive values towards yellow. The higher the value (either + or -), the more saturated a colour is. Each reading begun with a white tile to calibrate the instrument. The measurements taken were expressed in delta L*, delta a*, delta b* and delta E, representing the colour differences (i.e. +

or -) between the white tile and the individual sample. Delta E is the value that indicates the size of the colour difference considering L*, a* and b* in a single measurement, but does not indicate in what way the colour is different. At least 5 measurements were taken from each faecal sample, as not all samples were uniform in colour, which were eventually averaged. The starting point of the target (i.e. L*, a* and b* of the white tile) to which the samples were compared was recorded enabling true colour estimation. The latter was done by using the following formula:

True a* = a* (target, white tile) + delta a*

A similar formula was used for calculating the true directions of b*. Hue angle (H*) was calculated using the following formula (Konica Minolta, 2007):

$H^* = \tan^{-1}$ (true b*/true a*) [degrees]

The greenness represented by true a* and H* of creep feed was respectively (-7.38, SD = 0.15) and (121, SD = 0.812). Faeces appeared to be greener as pigs matured. Both true a* and H* values of piglets with no access to creep feed were significantly affected by experimental day (both $P < 0.001$) and a tendency was seen for an interaction between litter composition × experimental day ($P = 0.067$ and $P = 0.046$ respectively). To ensure that differences in true a* and H* were a result of the presence of chromic oxide, they were both corrected for day and treatment effects seen in non-creep litters, resulting in adjusted a* and adjusted H*ab using the following approach:

True a* from non-creep fed piglets was averaged per experimental day and litter composition. The latter, was subtracted from individual true a* observations of piglets reared in creep fed litters resulting in adjusted a*, using the following equation:

Adjusted a* = true a*(sample)-true a*(non-creep fed reference).

The non-creep fed reference is based on the average for each experimental day (d 13, 19, 21, 23, and 25) and for each litter composition (UNIFORM and MIXED) separately.

Adjusted a* obliterated the effect of experimental day ($P = 0.989$) and the interaction between experimental day × litter composition ($P = 0.939$) as previously seen in non-creep fed litters. It is therefore likely that any difference in adjusted a* found between piglets reared in creep fed litters, was the result of differences in creep feed consumption. Correcting H*, required adjusted a*, adjusted b* and adjusted C*ab. Adjusted C*ab represent the difference in Chroma, in which positive numbers indicate the sample being brighter than the reference sample and negative values the sample being duller. The following equations were used (Konica Minolta, 2007):

Adjusted H*ab = √((adjusted a*^2) + (adjusted b*^2)-(adjusted C*ab^2))

Adjusted C*ab = √[(adjusted a* "creep feed sample")^2 + (adjusted b* "creep feed sample")^2]- √[(adjusted a* "non-creep fed reference")^2 + (adjusted b* "non-creep fed reference")^2]

True b* was necessary for calculating adjusted C*ab and thus adjusted H*ab, but appeared to be significantly affected by experimental day ($P < 0.001$), birth weight class ($P = 0.0024$), and the interaction between litter composition × birth weight class ($P = 0.0487$). Therefore, true b* values had to be corrected using the following equation:

Adjusted b* = true b*(sample)-true b*(non-creep fed reference).

The non-creep fed reference was based on the average of each experimental day (d 13, 19, 21, 23, and 25), each litter composition (UNIFORM and MIXED) and each birth weight class (light and heavy) separately.

More specifically, true b* values of creep feed samples that were collected on d 21 from piglets born light and reared in UNIFORM litters (as an example), were corrected by subtracting the average non-creep fed reference of faeces collected on d 21 of light piglets reared in UNIFORM litters. Using the obtained adjusted b* for calculating adjusted H*ab, successfully diminished the effect of experimental day ($P = 0.217$), and the interaction experimental day × litter composition ($P = 0.700$) seen previously.

2.3.6 *Pre- and post-weaning performance*

Piglets were individually weighed at weaning (d 27.3, SD = 0.9 days of age), and those that had not reached a weaning weight of 4 kg were removed from the trial (Table 2.2). Additional weights were taken when pigs were moved to the grower facility (d 61.3, SD = 1.2), finisher facility (d 88.0, SD = 2.9) and the day before slaughter (d 164, SD = 13) to which most pigs (75%) were followed. To account for pigs that were of different size, ADG was scaled to body weight (g/day/kg BW). Up to 61 days of age pigs remained in the same litter group, enabling the estimation of feed intake (FI)/litter throughout the nursery phase (d 28-61).

2.3.7 *Statistical analysis*

The residual variance of the data were tested for normality using the UNIVARIATE procedure of SAS. Testing for normality showed skewed data for part of the dataset which were normalized (either by square root, log, cube root or inverse) and results were back transformed for presentation using a 95% confidence level. The homogeneity of variance was tested using the Levene's test and graphical diagnostics using PROC GLM. Data were expressed as least square means (LSM), also known as the estimated population marginal means and used in studies with unequal observations, and the corresponding approximate standard errors of the differences of means (SED) (Martinez and Bartholomew, 2017) unless stated otherwise. Statistical significance was assessed at the 5% level and tendencies were set at 10%.

A chi-square test was carried out to test whether the reason for removing pigs from the experiment or the number of piglets per creep consumer class was affected by litter composition (UNIFORM or MIXED) and birth weight class (light or heavy). Additionally, chi-square was used to determine the effect creep feed provision (yes or no) and sex on the number of piglets removed.

The effect of birth weight class (light or heavy) on the effect of litter composition on creep feed intake/piglet was estimated by one-way analysis of variance (ANOVA), using PROC GLM in SAS version 9.4 (SAS inst. Inc. Cary, NC), in which litter was the experimental unit. All other data were analysed using the PROC MIXED procedure and were blocked by farrowing batch.

Main effects of interest were litter composition, birth weight class and their interaction for all models. Except for post-weaning FI, creep feed provision did not significantly affect pre- and post-weaning performance and neither did it significantly interact with any other variable; it was therefore omitted from subsequent analysis and is not presented in the Results. Sex only significantly affected individual creep feed intake (i.e. feeding behaviour and the colorimetric method) and therefore was omitted from all other analysis. Initially, foster parity and pre-weaning litter size (adjusted litter size = [(Σ all the piglet hours piglets were suckling)/ 24 h]/weaning age in d) were added to model assessing pre-weaning performance, but were not significant and were therefore excluded from the final model. Experimental day was an independent factor in the models assessing individual and daily creep feed intake. The factors teat pair class and 'creep consumer' class were added to the models assessing their effect on pre- and post-weaning performance. Age was added to the model at d 88 and slaughter due to the variability in timing of transfer between stages. Several covariance structures (i.e. first-order auto regression, compound symmetry, and variance components) were tested. For the RANDOM effects the variance components resulted in the lowest Akaike information criteria.

The experimental unit for daily creep feed intake in g/day/piglet was litter average; average feed intake was calculated using the following formula: FI (g/day/piglet) = [(total amount consumed in g)/ total time (h) piglets spent with their foster sow] x 24 h. Piglet nested within litter was the experimental unit when assessing individual creep feed intake (i.e. feeding behaviour, consumer class, or the colorimetric method) and teat pair class at d 10. Since measurements for feeding behaviour and the colorimetric method were taken on subsequent days repeated measures were used. The covariance structure first-order regression was used in the REPEATED statement. In addition, the PDIFF option in the LSMEANS statement was used to separate means for testing the effect of different variables (i.e. consumer class and teat pair class) on subsequent performance.

The experimental unit for the pre- and post- weaning (d 0-61) performance was litter mean for light or heavy piglets. For UNIFORM litters, this was based on ~12 piglets either born light or heavy, and in the MIXED litters this was the mean of ~6 piglets separately for each birth weight class. Litter mean was blocked by sow nested within farrowing batch to account for light and heavy piglets in MIXED litters coming from the same litter. As the number of light and heavy between the different litter compositions varied (MIXED versus UNIFORM), a WEIGHT statement was added to the model using the actual number of piglets that were classified light or heavy. From d 61 pigs were mixed according to their size, therefore the experimental unit became pen mean, based on the number of light or heavy piglets within each group taking pre-weaning treatments (e.g. litter composition and creep feed provision yes or no) into consideration. Again a WEIGHT statement was used to account for differences in the number of pigs and pen was nested within farrowing batch. The coefficient of variation (CV) was only calculated from weaning up to d 61 as after that pigs were mixed

The Pearson correlation coefficient (r) was used to investigate whether creep feed intake was correlated with adjusted a*, adjusted H*ab and feeding behaviour, and whether colour reader measurements and pre-weaning performance were similarly correlated.

2.4 Results

There was no difference in the average parity number of sows between the different treatments ($P > 0.05$). Although cross-fostering created litters of 12 piglets/ sow, litter size decreased over time due to mortality and/ or the removal of piglets. Nevertheless, litter size at weaning was not influenced by litter composition (*P* > 0.05). Average litter size at weaning was 10.5 (SD = 1.7) for MIXED litters, 9.92 (SD = 1.31) for light piglets in UNIFORM litters and 10.9 (SD = 1.1) for heavy piglets in UNIFORM litters. Piglet sex was evenly distributed across treatments (i.e. litter composition, birth weight class and creep feed provision) with 46.9% being females and 53.1% being males (*P* > 0.05).

Table 2.2 The total number of pigs allocated and the number of pigs removed from the trial, with the reasons for their removal, according to litter composition and birth weight class: light (less than 1.25 kg) or heavy (1.50 to 2.00 kg) were in litters that consisted of same sized piglets (UNIFORM light or UNIFORM heavy) or of mixed sizes (MIXED: with both light and heavy).

Litter composition	UNIFORM		MIXED			
Birth weight class	LIGHT	HEAVY	LIGHT	HEAVY	Total	Significance[1]
Number of pigs on trial[2]						
d 0	144	144	77	77	154	
d 28	117	129	59	74	133	
d 61	116	129	59	74	133	
d 88	115	129	59	74	133	
d 165	98	109	54	64	118	
Number of pigs removed pre-weaning						
Found dead < 2 days of age	6 (4.2%)	0 (0.0%)	3 (3.9%)	0 (0.0%)	3 (2.1%)	0.027
Lost weight - removed < 10 days of age	14 (9.7%)	10 (6.9%)[a]	6 (7.8%)	1 (1.3%)[b]	7 (4.9%)	0.136
Found dead > 2 days of age < 28	5 (3.5%)	3 (2.1%)	5 (6.5%)	2 (2.6%)	7 (4.9%)	0.367
Under 4 kg at d 28	2 (1.4%)[a]	2 (1.4%)	4 (5.2%)[b]	0 (0.0%)	4 (2.8%)	0.083
Total	27 (18.8%)	15 (10.4%)[a]	18 (23.4%)	3 (3.9%)[b]	21 (14.6%)	0.001

[1] Data were analysed with a chi-square test.
[2] Pigs were weighed within 12 h after birth (d 0), at weaning (d 27.3, SD = 0.9), when moved to the grower (d 61.3, SD = 1.2) and finisher (d 88.0, SD = 2.9) facility. Not all pigs were followed to slaughter (d 164, SD = 13), due to farm practices
[a,b] Numbers within a row with different superscripts tended to differ statistically (*P* < 0.10).

Table 2.2 shows the total numbers used and the number of piglets removed from the trial, with the reasons for their removal, according to litter composition and birth weight class. Overall pre-weaning mortality was 5.4% from the time piglets were cross-fostered, excluding removals. There was no effect of creep feed provision on piglet mortality or the removal of piglets pre-weaning (*P* > 0.05). Piglet mortality up to 2 days post-partum was significantly affected by birth weight class (*P* = 0.027), with piglets born light having a higher mortality rate (either 3.9% or 4.2% for MIXED and UNIFORM litters respectively) than piglets born heavy (0%). Litter composition and birth weight class did not affect the number of piglets removed during early lactation (< d 10) as a result of losing weight, or the number of piglets that died between > 2 days post-partum and weaning. However, litter composition tended to affect (*P* = 0.066) the number of heavy piglets that had to be removed as a result of weight loss (< d 10), with heavy piglets in UNIFORM litters being removed in higher numbers (6.9%) than heavy piglets in MIXED litters (1.3%). The number of piglets removed from the trial weighing less than 4 kg at weaning tended to be influenced by litter composition and birth weight class ($P = 0.083$), with light piglets being removed in higher quantities. In addition, light piglets in MIXED litters tended ($P = 0.097$) to be removed at a higher rate (5.2%) than light piglets in UNIFORM litters (1.4%). Lastly, the total number of piglets removed from birth to weaning, was significantly ($P = 0.001$) affected by litter composition and birth weight class. A higher number of light piglets were removed compared with heavy piglets. Nevertheless, litter composition only affected the total number of heavy piglets, as heavy piglets in UNIFORM litters tended ($P = 0.091$) to be removed at a higher rate (10.4%) than heavy piglets in MIXED litters (3.9%).

2.4.1 *Behavioural observations*

Teat pair and teat consistency. Teat consistency score (C_i) was affected by experimental day ($P = 0.006$), as the percentage of piglets achieving a fixed teat pair (C_i=1) increased over time, being 71.9% on d 2 (SD = 21.5), 79.0% on d 5 (SD = 22.7), and 87.2% on d 10 (SD = 17.5). In addition, teat consistency was affected by litter composition ($P = 0.030$) on d 2, with piglets in UNIFORM litters having a significant lower teat consistency (65.9%, SD = 20.6) than piglets in MIXED litters (82.9%, SD = 19.4).

Table 2.3 shows the effect of piglet preferred teat pair class (i.e. anterior, middle, posterior teat pair), litter composition and birth weight class on pre-weaning performance. The three way interaction between litter composition × birth weight class × teat pair class significantly affected piglet body weight on d 10 ($P = 0.001$) and weaning ($P = 0.046$). Heavy piglets in UNIFORM litters were > 650 g and > 1500 g lighter on d 10 and weaning respectively, when sucking a posterior ($P < 0.001$) or middle teat pair ($P < 0.001$), compared with those sucking an anterior teat pair. In contrast, heavy piglets in MIXED litters were > 400 g lighter at 10 days of age when suckling a posterior teat than their similar sized littermates sucking an anterior ($P = 0.012$) or middle teat pair ($P = 0.038$). The latter difference was sustained throughout lactation, with heavy piglets sucking an anterior teat pair being 1000 g heavier at weaning than piglets suckling a posterior teat pair ($P = 0.046$). Teat pair preference did not influence ($P > 0.05$) light piglet body weight at 10 days of age in either litter composition. On the other hand, light piglets in UNIFORM litters sucking an anterior ($P = 0.005$) or middle teat pair ($P = 0.007$) were > 1000 g heavier at weaning than piglets suckling a posterior teat pair. Similarly, light piglets in MIXED litters sucking an anterior teat pair were > 700 g heavier at weaning, compared with piglets suckling a middle ($P = 0.066$) or posterior teat pair ($P = 0.075$). The three way interaction of litter composition × birth weight class × teat pair class also significantly affected ADG (g/day) between birth and 10 days of age (P =0.001) and tended to affect ADG between birth

Table 2.3 The effect of piglet preferred teat pair class, litter composition and birth weight class on pre-weaning performance: light (less than 1.25 kg) or heavy (1.50 to 2.00 kg) piglets were in litters that consisted of similar sized piglets (UNIFORM light or UNIFORM heavy) or of mixed weights (MIXED: with both light and heavy)[1]

Litter composition:	UNIFORM weights						MIXED weights							Significance[2]	
Birth weight class:	LIGHT			HEAVY			LIGHT			HEAVY					
Teat pair class[3]	Anterior (n=44)	Middle (n=55)	Posterior (n=20)	Anterior (n=45)	Middle (n=60)	Posterior (n=26)	Anterior (n=22)	Middle (n=34)	Posterior (n=7)	Anterior (n=29)	Middle (n=34)	Posterior (n=11)	SED	Teat pair class	Litter composition × birth weight class × eat pair class
Body weight, kg															
d 0	1.06	1.09	1.05	1.75	1.71	1.73	1.08	1.12	1.10	1.72	1.71	1.69	0.028	0.803	0.657
d 10	2.84	2.92	2.68	3.95^{a}	3.31^{b}	3.17^{b}	3.04	2.80	2.74	4.21^{a}	4.12^{a}	3.70^{b}	0.120	<0.001	0.001
d 28	7.48^{a}	7.39^{a}	6.35^{b}	8.88^{a}	7.35^{b}	7.00^{b}	7.33^{c}	6.59^{d}	6.17^{d}	9.35^{a}	8.93	8.30^{b}	0.310	<0.001	0.046
Average daily gain, d/day															
d 0-10	179	183	164	218^{a}	159^{b}	143^{b}	197^{c}	170^{d}	164	250^{a}	241^{a}	202^{b}	11.2	<0.001	0.001
d 0-28	234^{a}	229^{a}	194^{b}	259^{a}	204^{b}	194^{b}	233^{c}	204^{d}	189^{d}	284^{c}	267	250^{d}	11.1	<0.001	0.056

[1] Teat pair class was classified according to anatomical location of the teats (i.e. anterior, middle and posterior) and was assessed at 10 days of age. Data are expressed as LSM.

[2] In addition to the significant effect shown here, birth weight and the interaction between birth weight × litter composition significantly affected body weight at d 10 and d 28. Similarly ADG between birth and d 10 and birth and d 28 was affected by birth weight and birth weight × litter composition.

[3] The position at the udder was classified according to teat pair location: anterior (1-2), middle (3-5), and posterior (≥6).

[a,b] Within litter composition and birth weight class main treatment comparison (teat pair class), without a common superscript significantly differed (P < 0.05).

[c,d] Within litter composition and birth weight class main treatment comparison (teat pair class), without a common superscript tended to differ (P < 0.10).

and weaning ($P = 0.056$).

Teat pair class also significantly ($P < 0.001$) affected body weight at d 10 and weaning. Piglets sucking an anterior teat pair (respectively 3.51 kg, SD = 0.66 and 8.26 kg, SD = 1.67) were considerably heavier at d 10 and weaning than piglets sucking a middle teat pair (3.29 kg, SD = 0.69 and 7.57 kg, SD = 1.73) or a posterior teat pair (3.06 kg, SD = 0.58 and 6.97 kg, SD = 1.58). In addition, teat pair significantly influenced ADG from birth to 10 days of age ($P < 0.001$) and from birth to weaning ($P < 0.001$). Piglets sucking an anterior teat pair had a higher ADG between birth and 10 days of age, and birth and weaning (211 g/day, SD = 62 and 252 g/day, SD = 59 respectively), than those sucking a middle (188 g/day, SD = 65 and 226 g/day, SD = 61), or posterior teat pair (169 g/day, SD = 57 and 207 g/day, SD = 56).

Feeding behaviour. Feeding behaviour assessed at d 19, 21, and 25 was not affected by the interaction between litter composition × birth weight class ($P > 0.05$), litter composition ($P > 0.05$) or birth weight class ($P > 0.05$). Experimental day ($P < 0.001$) and sex ($P < 0.001$) significantly contributed to differences in feeding behaviour. Time spent at the feeder, expressed as total time spend at feeder/ piglet relative to the time recorded, increased over time, being 0.133% [95% CI 0.049, 0.215] at d 19, 0.183% [0.090, 0.325] at d 21, and 0.307% [0.174, 0.495] at d 25. Females (0.262% [0.146, 0.429]) spent more time at the feeder than males (0.133% [0.063, 0.242]).

2.4.2 *Creep feed intake*

Litter level. The interaction between litter composition × experimental day did not affect ($P > 0.05$) creep feed consumption g/day/piglet. Experimental day affected ($P < 0.001$) creep feed consumption (g/day/piglet) as shown on Figure 2.1. From d 18 onwards creep feed significantly ($P < 0.05$) increased over time. Most creep feed (85.1%, SD = 13.7) was eaten during the last week (d 20-27) before weaning. Litter composition also significantly ($P = 0.046$) influenced creep feed consumption: heavy piglets in UNIFORM litters consumed more feed over the total period (6.51 g/day/piglet [3.50, 11.54]), compared with light piglets ($P = 0.015$) raised with similar sized litter mates (2.00 g/day/piglet [0.78, 4.08]) or piglets of any birth weight class in MIXED ($P = 0.096$) litters (3.14 g/day/piglet [1.56, 5.69]).

Creep feed consumption correlated with adjusted a* ($r = -0.59$, $P < 0.001$), adjusted H*ab ($r = 0.64$, $P < 0.001$) and feeding behaviour ($r = 0.69$, $P < 0.001$). This indicates that litters consuming higher amounts of creep feed had lower adjusted a* and higher adjusted H*ab values, suggesting greener faeces, and spent more time at the feeder.

Individual piglet. Experimental day (P < 0.001) affected the number of visual colour-positive faecal samples collected, ranging from ~3% on d 13 and 16 to ~30% on d 21 and 23. More than half of the piglets had visibly green faeces at d 25 of age.

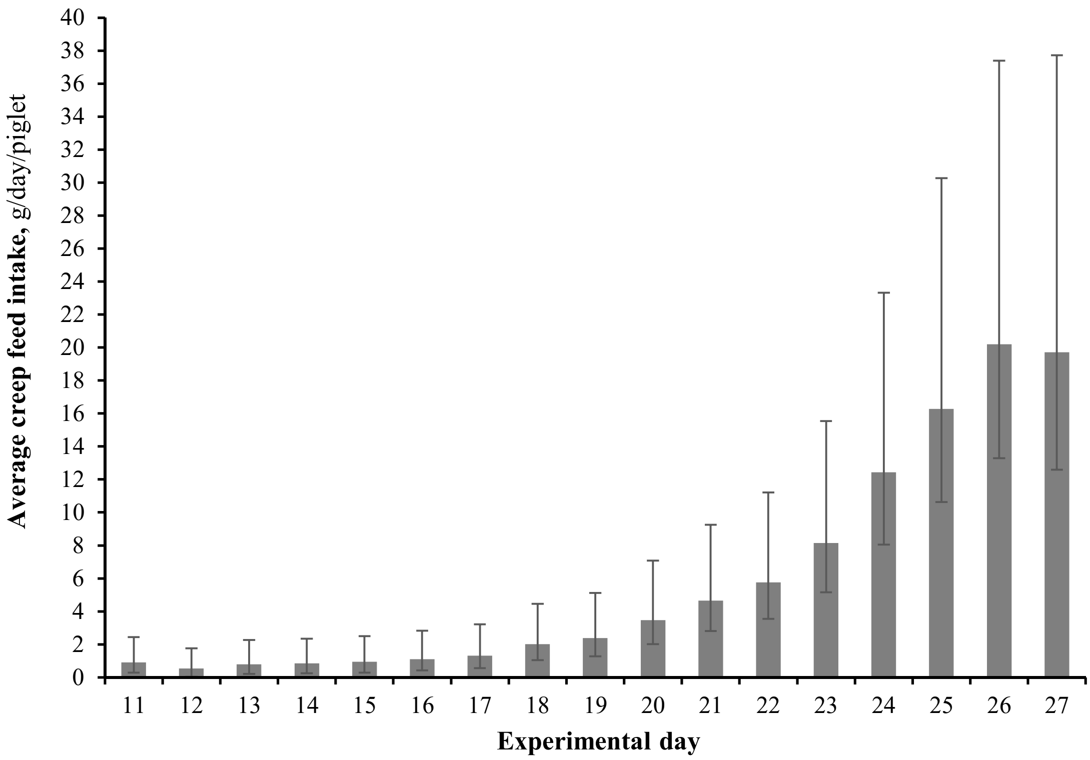


Figure 2.1 The effect of experimental day on creep feed intake (g/day/piglet) across litters. Pigs had access to ad libitum creep feed from d 10 of lactation up to weaning (d 27.3, SD = 0.9). Data are expressed as back transformed (log) least squares means, with error bars representing the 95% confidence interval.

The number of piglets classified as early consumers on d 19 was significantly (P < 0.001) affected by the interaction between litter composition × birth weight class. No differences (P > 0.05) were seen between the number of piglets born light that were classified as consumers and reared in either MIXED (18.5%) or UNIFORM litters (16.1%). However, more heavy piglets in UNIFORM litters (P = 0.014) were classified as consumers (34.3%) than those reared in MIXED litters (13.5%). Piglets showing visibly green faeces on d 19 tended (P = 0.053) to be lighter (5.07 kg, SD = 0.16) compared with piglets that did not show green faeces (5.53 kg, SD = 0.17). However, the effect of being classified as a consumer on d 19 did not significantly affected body weight at weaning (P > 0.05) nor did it affect (P > 0.05) ADG between d 19 and weaning (consumer 273 g/day, SD = 81 versus non-consumer 277 g/day, SD = 99).

Table 2.4 summarizes the total number of piglets classified as either non-consumer or consumer (low, moderate, or high) for piglets born light and heavy, and either reared with similar sized piglets or in litters of MIXED weights. The number of piglets classified as non-consumers was significantly affected (*P* = 0.002) by the interaction between litter composition × birth weight class. A lower proportion (*P* = 0.006) of non-consumers was seen for piglets born heavy in UNIFORM litters (27.3%) compared with heavy piglets in MIXED (53.6%) litters. However, the fraction of light piglets classified as non-consumers was generally high, irrespectively of litter composition. Furthermore, the number of piglets classified as high consumers tended to be different (*P* = 0.064) with piglets being born heavy and reared in UNIFORM litters having the highest number of piglets classified as consumers (18.2%) and light piglets in UNIFORM litters the lowest (4.7%).

Table 2.4 Total number of piglets classified as either non consumers or consumers (low, moderate, or high) of creep feed for piglets born light (less than 1.25 kg) and heavy (1.50 to 2.00 kg) and either reared with similar sized piglets (either light or heavy, UNIFORM) or in litters with MIXED weights (both light and heavy)[1]

Litter composition	UNIFORM		MIXED		
Birth weight class	LIGHT (*n*=64)	HEAVY (*n*=66)	LIGHT (*n*=33)	HEAVY (*n*=41)	Significance[2]
High consumer	3 (4.7%)	12 (18.2%)	2 (6.1%)	4 (9.8%)	0.064
Moderate consumer	12 (18.7%)	10 (15.1%)	3 (9.1%)	4 (9.8%)	0.474
Low consumer	16 (25.0%)	26 (39.4%)	7 (21.2%)	11 (26.8%)	0.174
Non consumer	33 (51.6%)	18 (27.3%)[a]	21 (63.6%)	22 (53.6%)[b]	0.002

[1] Piglets scoring positive (visually green faeces) for all three sampling days (i.e. d 19, 21, and 25), were classified 'high consumer'. Piglets having green faeces at two out of the three occasions were categorized 'moderate consumer' and 'low consumer' had green faeces at one occasion. Non-consumer were piglets that never scored positive on the sampling days.
[2] Data were analysed with a chi-square test.
[a,b] Within main treatment comparison (litter composition or birthweight category), counts without a common superscript tended to differ (*P* = 0.006).

The effect of consumer class on pre- and post-weaning performance is summarized in Table 2.5. Consumer class significantly affected piglet body weight on d 19 (*P* = 0.039). Animals classified as moderate and high consumers were > 750 g lighter on d 19, than those classified as low (*P* < 0.05) or non-consumers (*P* < 0.05). In addition, consumer class tended (*P* = 0.089) to affect body weight at weaning. Piglets classified as moderate consumers (7.01 kg, SD = 1.85) were > 800 g lighter at weaning, than piglets classified as non- (7.85 kg, SD = 1.61; *P* = 0.029) or low consumers (7.79 kg, SD = 1.70; *P* = 0.058). Average daily gain from birth to 19 days of age was significantly affected (*P* = 0.023) by consumer class. Piglets classified as moderate and high consumers gained significantly less than low (*P* < 0.10) and non-consumers (*P* < 0.05). However, consumer class did not affect (*P* > 0.05) ADG from d 19 to weaning: piglets classified as moderate (245 g/day, SD = 90) and high consumers (262 g/day, SD = 99) performed similar to those classified as non- (273 g/day, SD = 95) or low consumer (276 g/day, SD = 93). In addition, consumer class tended (*P* = 0.089) to affect ADG between birth and weaning, in which

Table 2.5 The effect of 'consumer' class on pre- and post-weaning performance. Piglets were classified as either non consumer or consumers (low, moderate, or high) of creep feed and those scoring positive (visually green faeces) for all three sampling days, were classified high consumers[1]

	Consumer class					
	Non consumer	Low consumer	Moderate consumer	High consumer	SED	Significance[2]
Body weight, kg						
d 0	1.38	1.41	1.40	1.41	0.013	0.896
d 10	3.31	3.34	3.13	3.15	0.053	0.573
d 19	5.58[aA]	5.54[aB]	4.98[b]	4.82[b]	0.089	0.039
d 28	7.85[a]	7.79[c]	7.01[bd]	7.08	0.123	0.089
d 61[3]	22.1	22.3	21.5	23.0	0.335	0.597
Average daily gain, g/day						
d 0-19	221[a]	218[aA]	188[bB]	179[b]	4.44	0.023
d 19-28	273	276[A]	245[B]	262	5.93	0.353
d 0-28	238[a]	235[A]	208[bB]	210	4.36	0.084
d 28-61	407[a]	420[a]	411[a]	484[b]	10.5	0.051

[1] All piglets reared in creep feed litters had access to creep feed containing chromic oxide from 10 days of age up to weaning at approximately d 28 (d 27.3, SD = 0.9). Visibly green faeces indicated that the piglet had eaten creep feed. Faecal samples were taken and visually assessed during three days (d 19, 21, and 25). Piglets having green faeces at two out of three occasions were categorized moderate consumers and low consumers had green faeces at one occasion. Non consumers were piglets that never scored positive on the sampling days. Data are expressed in LSM.
[2] In addition to the significant effect shown here, birth weight and the interaction between birth weight × litter composition significantly affected body weight and ADG at the different stages of production.
[3] Piglets remained in the same litter from birth, weaning (d27.3, SD = 0.9) to d 61 (d 61.3, SD = 1.2).
[a,b] Within main treatment comparison (creep feed eater class), counts without a common superscript significantly differed ($P < 0.05$).
[A,B] Within main treatment comparison (creep feed eater class), counts without a common superscript tended to differ ($P < 0.10$).

only moderate consumers seemed to be affected by gaining less than low ($P = 0.064$) and non-consumers ($P = 0.027$). Although consumer class did not significantly affect ($P > 0.05$) body weight once they reached grower age (d 61), piglets classified as high consumers were numerically heavier (Table 2.5). On the other hand, consumer class tended to affect ADG between weaning and 61 days of age ($P = 0.051$) with piglets classified as high consumers gaining significantly more than piglets classified as non- ($P = 0.006$), low ($P = 0.029$) or moderate consumer ($P = 0.025$).

Creep estimate through the colorimetric method. The average faecal colour (95% confidence interval) of piglets that had no access to creep feed was 0.00 [-0.12 to 0.12] for adjusted a* and 1.57 [1.49, 1.65] for adjusted H*ab. The interaction between litter composition × birth weight class ($P = 0.022$) significantly affected adjusted a*. Piglets born heavy and reared in UNIFORM litters had significantly ($P = 0.018$) greener faeces (-1.76, SD = 2.37) than similar sized piglets in MIXED litters (-0.60, SD = 2.15). In contrast, adjusted a* for light piglets reared together with heavier litter mates was only numerically lower (-0.58, SD = 2.33) than for piglets born light but reared in UNIFORM litters (-0.33, SD = 2.42), implying that light piglets in MIXED litters did not have greener faeces than those in UNIFORM litters. Sex significantly interacted ($P = 0.031$) with birth weight class, whereby light females (-0.84, SD = 2.55) had significantly ($P < 0.001$) greener faeces than light males (-0.07, SD = 2.14). Females born heavy only had numerically greener faeces (-1.27, SD = 2.43) than their similar sized males (-1.08, SD = 2.21). The interaction between sex × experimental day also significantly affected adjusted a* ($P < 0.001$) in which females started to have significantly greener faeces from d 19 onwards ($P < 0.05$). Also, experimental day as main effect significantly affected the greenness of faeces ($P < 0.001$) of creep fed piglets in which adjusted a* became more negative over time, with 0.38 (SD = 2.43) at d 13, -0.14 (SD = 2.23) at d 16, -0.63 (SD = 2.27) at d 19, -1.23 (SD = 3.29) at d 21, -1.42 (SD = 2.20) at d 23, and -1.85 (SD = 2.38) at d 25. In addition, birth weight class significantly contributed to differences in adjusted a* ($P = 0.017$) where heavy piglets had greener faeces (-1.18, SD = 2.32) compared with piglets born light (-0.46, SD = 2.40). Sex significantly ($P < 0.001$) affected adjusted a*, as females had greener faeces (-1.06, SD = 2.51) than males (-0.57, SD = 2.22). Adjusted a* was not affected by teat pair class ($P > 0.05$).

Adjusted H*ab was not affected by the interaction between litter composition × birth weight class ($P > 0.05$), litter composition ($P > 0.05$) or birth weight class ($P > 0.05$). Adjusted H*ab was significantly affected by experimental day ($P < 0.001$), increasing over time from 1.73 [1.37, 2.13] at d 13 to 2.15 [1.76, 2.59] at 25 days of age. In addition, sex significantly ($P = 0.030$) contributed to differences in adjusted H*ab: faeces of females (1.94 [1.60, 2.30]) were greener than those of males (1.71 [1.40, 2.06]). Teat pair class significantly ($P = 0.021$) affected adjusted H*ab: piglets suckling the anterior teats had less green faeces (1.62 [1.31, 1.96]) than those suckling the middle (1.88 [1.56, 2.24]) or posterior teat pair (1.98 [1.57, 2.44]).

Although significant ($P<0.05$), correlations between the colour readings (i.e. adjusted a* and adjusted H*ab) and pre-weaning performance were generally weak ($r < 0.30$; Taylor 1990). Scaled ADG (g/day/kg BW) between birth and 19 days of age positively correlated ($P < 0.05$) with adjusted a* on subsequent sampling days (i.e., d 21, 23, and 25) ranging between $r = +$ 0.20 to + 0.35. The opposite was true for adjusted H*ab, resulting in negative correlations ($P<0.05$) ranging between $r = -0.28$ and -0.19. On the other hand, during the last week before weaning, from d 19 to 28, piglets that had green faeces, represented by lower adjusted a* at either d 21, 23 or 25, gained more g/day/kg BW (r ranging between -0.21 and -0.24; $P < 0.05$). A similar effect ($P < 0.05$) was seen for adjusted H*ab, resulting in positive correlations at d 21, 23 and 25 between adjusted H*ab and scaled ADG from d 19 to weaning, ranging between $r = +$ 0.17 and + 0.29.

2.4.3 *Pre- and post-weaning performance*

As creep feed provision did not influence performance at any stage of production nor interact with litter composition or birth weight class, creep feed treatment was removed from subsequent analyses. When all piglets weaned were included, the interaction between litter composition × birth weight class ($P < 0.001$) significantly influenced weaning weight. Piglets born light and reared in UNIFORM litters were 600 g heavier at weaning compared with similar birth weight piglets in MIXED litters (7.29 kg, SD = 0.60 versus 6.67 kg, SD = 0.85). The opposite was true for heavy piglets, weighing more than 1 kg heavier when reared in MIXED litters compared with those in UNIFORM litters (8.93 kg, SD = 0.79 versus 7.86 kg, SD = 0.57).

Table 2.6 shows the effect of litter composition, birth weight class and their interaction on the performance of piglets born light and heavy from birth to slaughter at different stages of production; these results include only piglets weaned heavier than 4 kg. The interaction between litter composition × birth weight class ($P < 0.001$) significantly influenced piglets body weight at ~28 days of age. Piglets born light were 400 g heavier at weaning when reared in UNIFORM litters than in MIXED litters. When considering the effect of littermate weight on piglets born heavy, piglets from MIXED litters were almost 1 kg heavier at weaning compared with those reared in UNIFORM litters. Similarly, ADG ($P < 0.001$) and scaled ADG ($P < 0.001$) from birth to weaning was significantly affected by the interaction between litter composition × birth weight class. Piglets born light and reared in UNIFORM litters gained more compared with those in MIXED litters, the opposite was true for piglets born heavy. Furthermore, birth weight class affected body weight at weaning ($P < 0.001$) with piglets born light being 1.3 kg lighter than piglets born heavy (7.11 kg, SD = 0.64 vs. 8.40 kg, SD = 0.59). Total litter gain between birth and weaning was not affected by litter composition ($P = 0.565$); UNIFORM litters gained 64.6 kg (SD = 12.9) and MIXED litters 66.7 kg (SD = 11.0).

Body weight at d 61, 88, and the day before slaughter was significantly ($P < 0.05$ or $P < 0.10$) affected by the interaction between litter composition × birth weight class. The weight advantage heavy piglets had at weaning when reared in MIXED litters increased to 1.5 kg when they reached grower weight (~d 61), 2.8 kg when they reached finisher weight (~d 88) and almost 2.5 kg by the day before slaughter. Also for piglets born light and reared in different litter compositions, the

Table 2.6 The effect of litter composition (UNIFORM vs. MIXED) and birth weight class and their interaction on the performance of piglets born light (less than 1.25 kg) and heavy (1.50 to 2.00 kg) from birth to slaughter at different stages of production (weaner, grower, finisher, slaughter)[1]

Litter composition:	UNIFORM weights		MIXED weights			Significance[2]		
Birth weight class:	LIGHT	HEAVY	LIGHT	HEAVY	SED	Birth weight class	Litter composition	Litter composition × birth weight class
Body weight, kg								
d 0[2]	1.06 [1.04, 1.09]	1.72 [1.69, 1.76]	1.10 [1.06, 1.13]	1.70 [1.66, 1.75]		<0.001	0.411	0.093
d 28	7.37	7.96	6.93	8.93	0.099	<0.001	0.137	<0.001
d 61	20.9	23.7	20.5	25.2	0.337	<0.001	0.282	0.072
d 88	36.2	39.5	35.1	42.3	0.595	<0.001	0.326	0.020
d 165	97.1	98.7	93.4	101	1.05	0.001	0.684	0.018
Average daily gain, g/day								
d 0-28	264	280	252	324	3.97	<0.001	0.032	<0.001
d 28-61	393	454	393	470	7.79	<0.001	0.596	0.570
d 61-88	575	592	541	634	17.6	0.009	0.841	0.064
d 88-165	777	778	754	780	11.0	0.299	0.415	0.327
Scaled ADG, g/day/kg BW								
d 0-28	245	162	229	188	5.20	<0.001	0.402	<0.001
d 28-61	55.8	57.7	52.9	51.4	2.61	0.940	0.140	0.561
d 61-88[3]	25.8 [22.0, 31.3]	23.8 [20.5, 28.4]	24.6 [20.8, 30.0]	23.6 [20.2, 28.3]		0.115	0.459	0.600
d 88-165	21.7	20.8	22.6	19.6	0.540	<0.001	0.724	0.048
CV								
d 28	18.2	19.9	21.3	14.2	0.847	0.082	0.409	0.007
d 61	13.1	11.8	12.9	9.7	0.927	0.077	0.359	0.442

[1] Light and heavy piglets were in litters that consisted of same sized piglets (either light or heavy, UNIFORM) or of mixed sizes (MIXED: with both light and heavy). Data are expressed in LSM or stated otherwise. Piglets remained in the same litter from birth to d 61 after which they were randomly mixed according to their size. Pigs were weighed at birth d 0, when weaned (d 27.3, SD = 0.9), when moved to the grower facility (d 61.3, SD = 1.2), when moved to finisher accommodation (d 88.0, SD = 2.9), and when reaching slaughter weight (d 164.2, SD = 13).

[2] Data are expressed as back transformed (log) LSM with 95% confidence interval

[3] Data are expressed as back transformed (inverse) LSM with 95% confidence interval

effect of litter composition on body weight was sustained throughout production, with 400 g difference at d 61, 1.1 kg at d 88, and piglets were almost 3.7 kg heavier when they reached slaughter age, when reared in UNIFORM litters. The interaction between litter composition × birth weight class did not ($P > 0.05$) influence ADG nor scaled ADG during nursery (d 28-61) or grower phase (d61-88). Total group gain between weaning and grower, during which pigs remained in the same pre-weaning group, was not affected by litter composition ($P = 0.570$), pens of UNIFORM litters had a total group gain of 143 kg (SD = 45) and pens of MIXED litters 136 kg (SD = 37). Teat pair class affected post-weaning performance ($P = 0.002$). Piglets sucking an anterior teat pair class had a significantly lower scaled ADG (53.7 g/day/kg BW, SD = 18.2) between weaning and grower phase than those sucking a middle (61.4 g/day/kg BW, SD = 18.1) or posterior teat pair (64.6 g/day/kg BW), SD = 18.2).

Birth weight class significantly affected body weight at the different weighing points (i.e. d 61, 88, and 165) and ADG from weaning to 9 weeks of age ($P < 0.001$) and from d 61 to 88 ($P = 0.009$). Piglets born light were 4 kg lighter when they reached the grower stage (20.9 kg, SD = 2.2 vs. 24.8 kg, SD = 2.0), 5 kg lighter when they reached the finisher stage (35.7 kg, SD = 5.9 vs. 40.9 kg, SD = 5.8), and 5 kg lighter on the day before slaughter than piglets born heavy (95.3 kg, SD = 10.8 vs. 100 kg, SD = 10.0). In addition, birth weight class significantly affected ($P = 0.031$) slaughter age, whereby light piglets were generally older at slaughter (166 [158, 177] vs. 162 [155, 170] days of age) than piglets born heavy.

Table 2.6 presents the effect of litter composition and birth weight class and their interaction on the coefficient of variance (CV) from weaning to grower. There was no main effect of litter composition on CV. Only at weaning was the CV significantly influenced by an interaction between birth weight class × litter composition ($P = 0.007$). Piglets born light and reared together with heavier littermates (MIXED litters) had a numerically higher CV compared with those in UNIFORM litters; the opposite was true for heavy piglets ($P = 0.009$). Birth weight class tended to affect CV at d 28 ($P = 0.082$) and d 61 ($P = 0.077$). Piglets born light had a higher CV at birth, weaning and when they reached the grower stage (d 61). Litter CV of heavy piglets at weaning was furthermore affected ($P = 0.051$) by creep feed provision. Heavy piglets having access to creep feed had a lower CV (15.2, SD = 5.0) than heavy piglets without creep feed (19.4, SD = 5.2).

During the nursery stage (d 28-61) piglets stayed in the same pre-weaning litter group, enabling the estimation of feed intake (FI)/litter. Litter composition ($P = 0.002$) significantly influenced daily FI when expressed per piglet. Heavy pigs in UNIFORM litters consumed the highest amount of feed, followed by MIXED litters. The lowest amount of weaner feed was consumed by light pigs in UNIFORM litters. Furthermore, numerical differences were found for creep feed provision on post-weaning daily intake ($P > 0.05$). Pigs that had access to creep feed pre-weaning ate more of the weaner feed (647 g/day/piglet, SD = 55) than pigs raised without it (616 g/day/piglet, SD = 53).

2.5 Discussion

The high level objective of this work was to develop strategies to deal with the challenge of piglets born lightweight. Piglets born light can either be born small for gestational age or have experienced intra-uterine growth restriction (Rutherford et al., 2013). Although, different definitions are considered in the literature the consistent view is that lightweight piglets have a significantly lower pre-weaning survival rate (58 % vs. 92 %) (Jourquin et al., 2016), need 7 to 14 days extra to reach slaughter weight (105 kg) compared with piglets weighing respectively 1.50 or 2.00 kg at birth (Quiniou et al., 2002), and have a poorer feed efficiency (Gondret et al., 2006). Schinckel et al. (2007) predicted that for piglets with a birth weight of 1 kg, a 0.1 kg increase in birth weight reduced the days to reach 105 kg by 2.86, implying that the extra days needed to reach slaughter weight can be even more. Taking into consideration that around 15% of the newly born piglets weigh less than 1.11 kg at birth (Feldpausch et al., 2016) and that pigs are mostly sold on weight specifications rather than age, this results in batch inefficiency. This might be even more detrimental in very high prolific sows, as the number of small piglets increases with increasing litter size, with small pigs (< 1.00 kg) representing <10% of the population in litter sizes of ≤ 13 piglets, and 23% in litter sizes of > 15 piglets (Quiniou et al., 2002; Quesnel et al., 2008; Beaulieu et al., 2010a). In our herd, 10% of the piglets weighed less than 1 kg at birth, and 25% weighed less than 1.25 kg. There is now consistent evidence to suggest that light piglets benefit from cross-fostering that creates uniform litters, by improving pre-weaning performance (English and Bilkei, 2004; Douglas et al., 2014c) and reducing pre-weaning mortality (Milligan et al., 2001; Deen and Bilkei, 2004). However, it is currently unknown what the consequence of this practice is for the performance of normal or heavy weight piglets and therefore its effectiveness in reducing batch variation. One can hypothesize that uniform litters comprising of only heavy piglets would result in high competition for the more productive teats and an increased indirect competition: stimulating teats essential for subsequent milk withdrawal. Thus their short or long term performance may be penalized. One way of overcoming this may be through the provision of creep feed. The specific objectives of this experiment were based exactly on this thought process; we focused on light and heavy pigs to exaggerate the contrast for the effects of cross-fostering. We aimed to investigate the effect of litter composition and creep feed availability on lifetime performance of piglets born light and heavy. It was further hypothesized that creep feed provision will convey some benefits on the light piglets, but these would be to a lesser extent than on heavy piglets, since the consumption of creep feed seems to be dependent on whether milk consumption is sufficient to support piglets growth. Lastly we expected that these benefits on the performance as a result of cross-fostering and creep feed provision would be seen in the long term, i.e. to slaughter.

There has been some doubt about the beneficial effects of cross-fostering on piglets born light (Milligan et al., 2001). Our results, consistent with those of others (Deen and Bilkei, 2004; Douglas et al., 2014c), suggest that UNIFORM litters benefit piglets born light, which exhibit higher weaning weights than similar sized piglets in MIXED litters. In addition, light piglets in MIXED litters tended to be removed in greater quantities for being too light (< 4kg) at weaning then when reared in UNIFORM litters. It has to be noted however, that in our study litter sizes were relatively small (~12 piglets), and that in large litter sizes of the very high prolific sow (>15 piglets) the positive effect litter uniformity had on light piglets performance as shown here, might be less apparent. There are several possible explanations for the weight disadvantage light piglets exhibit when reared together with heavy piglets and its effect on weaning weight. First, rearing light piglets in MIXED litters would negatively influence their ability to directly compete for the more productive anterior teats (Scheel et al., 1977; Mason et al., 2003; Drake et al., 2008). Generally, teat position affects pre-weaning performance with piglets sucking a posterior teat having a lower milk intake than those sucking an anterior or middle teat (Skok et al., 2007). The latter, seems especially apparent in multiparous sows, rather than primiparous sows where neither differences in teat development nor piglet performance were observed (Nielsen et al., 2001). Second, light piglets could be disadvantaged indirectly through their size in the stimulation of teats essential for subsequent milk let down (King et al., 1997; Drake et al., 2008), which depends on the intensity and duration of massaging (Gill and Thomson, 1956). The absence of indirect competition in UNIFORM litters might have resulted in a greater share in the available milk and improved performance of light piglets. In our study, however, teat pair preference was not affected by birth weight. Although, we did not look at total milk intake, it is unlikely that direct competition have contributed to the impaired performance of light piglets reared in MIXED litters. The weight advantage light piglets had at weaning when reared with similar sized piglets was sustained throughout production, as suggested by Klindt (2003) and Douglas et al. (2014c).

Piglets gaining less during early lactation, for example by suckling the posterior teats or retrieving an unequal share from the available milk, may be expected to eat larger amounts of creep feed (Algers et al., 1990; Appleby et al., 1992). In addition, Sulabo et al. (2007) suggested that the probability to become a non-consumer increased with increasing birth weight. Also in our work piglets classified as moderate and high consumers were generally the lightest at 19 days of age, suggesting that creep feed consumption is dependent on whether the amount of milk consumed is sufficient to support requirements for growth. It was therefore expected that light piglets in MIXED litters would consume higher amounts of creep feed to compensate for their insufficient milk intake. However, our findings suggest that piglets born light, irrespectively of litter composition, hardly consumed any creep feed, represented by a high proportion of piglets classified as non-consumer and faeces being less green. Their (low) milk intake might have been sufficient (Pajor et al., 1991) for their reduced growth capacity, as a result of nutrient restriction in utero (Foxcroft et al., 2006). Another explanation for their low creep feed consumption, could be their less mature digestive system represented by a lower trypsin (Cranwell et al., 1997; Pluske et al., 2003; Michiels et al., 2013) and lipase activity (Pluske et al., 2003) per g of pancreas compared with heavier piglets. In addition, heavy piglets in MIXED litters might have had a competitive advantage for the access to the creep feeder (Pajor et al., 1991; Bøe and Jensen, 1995), all of which could have contributed to the absence of substantial creep feed consumption by light piglets demonstrated here.

Cross-fostering has been reported to decrease pre-weaning mortality of piglets born light (Milligan et al., 2002; Deen and Bilkei, 2004; Cecchinato et al., 2008) by limiting competition for teat accessibility and thus essential resources. This suggestion was not confirmed here or in some other trials (Douglas et al., 2014c). Previous studies suggesting a beneficial effect of litter uniformity on mortality (Milligan et al., 2001; Deen and Bilkei, 2004), have classified light piglets as weighing less than 1 kg and applied cross-fostering within 12 h after birth. Survivability, however, decreases with decreasing birth weight: piglets weighing less than 1.10 kg have a significantly lower survivability (Feldpausch et al., 2016; Jourquin et al., 2016). Furthermore, performance and birth weight are negatively related (Paredes et al., 2012; Douglas et al., 2013), and moving piglets too early might have deprived piglets of access to colostrum (Baxter et al., 2013), which is important for survivability (Devillers et al., 2011). In addition, Deen and Bilkei, (2004) suggested that survivability of light piglets might not solely be dependent on litter mate weight but that litter size also play a prominent role in pre-weaning mortality. Low litter sizes however are hard to maintain in herds with very high prolific sows. Our protocol involving milk supplementation and creep training during the most critical period post-partum (< d 4), has most likely contributed to the absence of litter mate weight effect on pre-weaning mortality.

The consequences of creating litters with less weight variability on the performance of piglets born heavy have often been neglected. This is surprising as one needs to know the consequences on the performance of all pigs in a system in order to assess the effectiveness of a management strategy. Whilst expected that litter composition would not affect pre-weaning performance of piglets born heavy or any disadvantages would be compensated by the provision of creep feed, piglets born heavy and reared in UNIFORM litters were weaned almost 1 kg lighter than similar sized piglets in MIXED litters, irrespective of creep feed provision.

The negative effect litter mate weight had on pre-weaning performance of piglets born heavy could have been a result of: 1) increased direct competition for the more productive teats in litters with less weight variability, decreasing teat consistency (Baxter et al., 2013; Hales et al., 2013) and 2) the positive association between birth weight and piglet efficiency of massaging and draining teats (King et al., 1997), that could give heavy piglets a weight advantage when reared with light piglets (MIXED litters). Sizing piglets for body weight may have led to more aggression (Arnott and Elwood, 2009) and consequently more disputes and missed suckling bouts (Milligan et al., 2001). In our study teat consistency was affected by litter composition at 2 days of age. Litters with less weight variability (UNIFORM), irrespective of birth weight, had a lower teat consistency. Although piglets generally explore the entire udder during early lactation (Skok and Škorjanc, 2014), decreasing weight variability may have intensified competition, thus decreasing teat consistency (Baxter et al., 2013; Hales et al., 2013). However, teat ownership is often established shortly after birth as delaying teat cohesion compromises survival (Skok and Škorjanc, 2014). This most likely explains why the effect of litter composition on teat consistency was not sustained in the long term.

In addition, our results demonstrated that heavy piglets in UNIFORM litters tended to be removed in higher quantities during the first 10 days of life as a result of subsequent weight loss compared with heavy piglets in MIXED litters. These pigs most likely were involved in teat disputes or unable to access and adequate teat and therefore lost weight. Although, heavy piglets in MIXED litters were only significantly disadvantaged when suckling the posterior teat pair, heavy piglets in UNIFORM litters were disadvantaged when suckling both the posterior and middle teats. Milk yield varies with parity, the highest milk yield is seen for sows of parity 2 to 4 after which it decreased (Dourmad et al., 2012). In addition, differences between performance of piglets sucking the anterior and posterior teat seem to increase with increasing parity (parity 2 versus 3-4) (Dyck et al., 1987). Given that this study used older sows, milk yield and preferred teat position could have substantially limited their performance. Nevertheless, this suggests that; 1) the weight advantage heavy piglets had in MIXED litters resulted in an unequal milk distribution across teats favouring the heavier piglets; and 2) the increase in indirect competition for heavy piglets in UNIFORM litters resulted in less milk intake per piglet.

It was furthermore observed that the weight advantage heavy piglets had in MIXED litters was sustained during the different phases of production. Whilst, it could have been argued that piglets are able to compensate growth once restrictions are eliminated, it has been suggested that nutrient intake during suckling 'sets' animals' appetite during later life (Hales and Barker, 2001). In addition, keeping littermates together during nursery (d 28-61) could have given heavy piglets in MIXED litters a competitive advantage for the feeder, whilst the relatively lower space allowance for heavy pigs in UNIFORM litters could have restricted their growth (Vermeer et al., 2014).

To our knowledge, this is the first study that has investigated the effect of different litter compositions on creep feed disappearance. Although, chromic oxide is commonly used to discriminate between consumers and non-consumers of creep feed, the absence of the dye does not necessarily rule out that the piglet has eaten creep feed. Small amounts of creep feed could have been diluted by a high amount of milk (Barnett et al., 1989; Kuller et al., 2007a) and, when consumed for only 1 day, be difficult to detect (Kuller et al., 2007c), therefore in this study a colour reader was used to objectively assess faecal colour. Creep feed consumption is believed to be influenced by litter mates, as individuals that start eating creep feed could motivate unexperienced piglets within the same litter (Oostindjer et al., 2014), and by teat position, with piglets suckling the posterior teats eating larger amounts of creep feed (Algers et al., 1990). The latter was supported by our data, as faecal colour was significantly affected by teat pair class: faeces of piglets suckling the anterior teats were perceived less green. The results presented here demonstrated that litter composition influenced creep feed consumption, with heavy piglets in UNIFORM litters consuming the highest amount of creep feed and having the greenest faeces. In addition, a significantly higher number of heavy piglets reared in UNIFORM litters were already consuming creep feed by d19, as well as a lower proportion of heavy piglets being classified as non-eater compared with heavy piglets in MIXED litters and light piglets in UNIFORM and MIXED litters. The increased competition for heavy piglets in UNIFORM litters, leading to insufficient milk intake, might have driven these piglets to consume more creep feed.

Consistent with the results of Sulabo et al. (2007), Collins et al. (2013), and Blavi et al. (2015) creep feed provision did not influence weaning weight nor did it contribute to an improved litter

CV at weaning. However, not every piglet consumed creep feed, and more than half of the creep feed was eaten during the last week prior weaning, as shown in our work and that of others (Barnett et al., 1989; Bruininx et al., 2002). Although high and moderate consumers gained less weight during most of the suckling period, and were lighter one week prior to weaning, consumer class did not affect piglets' weaning weight nor ADG between d19 and weaning. The latter suggests that high consumers were able to catch up in growth. In addition, once creep feed was consumed in sufficient quantities, it tended to decrease variation at weaning as illustrated by the lower CV for heavy piglets. Appleby et al. (1992) found a negative correlation between ADG during the initial 3 weeks of lactation and feeding score and a positive correlation between feeding score and ADG between d 21 and 28. The latter was supported by the colorimetric results of the present study and of Kuller et al. (2007a). Being a high consumer pre-weaning is also believed to positively affect piglets post-weaning performance. Various studies have shown that piglets classified as high consumers performed better during the most critical period post-weaning by starting to eat sooner (Bruininx et al., 2002), gaining weight faster (Collins et al., 2013; Blavi et al., 2015) and having a decreased risk for post-weaning diarrhoea (Kuller et al., 2007b) compared with those classified as non-eaters. Also, in the current study ADG between weaning and grower phase of piglets classified as high consumers was significantly higher than for piglets classified non-, low, or moderate consumers.

2.6 Conclusion

The present study tested the effectiveness of cross-fostering as a management strategy by offsetting the effect cross-fostering had on piglets born light to that on piglets born heavy. The results presented here demonstrate that light piglets in UNIFORM litters were weaned 6% heavier and removed in lower quantities (-4.6%) than light piglets in MIXED litters. This weight advantage was evident to slaughter. Although litter uniformity successfully improved pre- and post- weaning performance of piglets born light, birth weight played a greater role in subsequent performance (Douglas et al., 2014c), with light piglets needing 4 extra days to reach slaughter weight than piglets born heavy.

On the other hand, heavy piglets in UNIFORM litters were 12% lighter at weaning than those reared in MIXED litters. The overall removal of heavy piglets in UNIFORM litters was considerably higher (+6.5%) than that in MIXED litters. Although, pre-weaning litter gain was not affected by litter composition, also here weight differences were sustained throughout production, with heavy piglets from UNIFORM litters being 6.0%, 6.6% and 2.3% lighter at respectively grower, finisher and slaughter stages. The results imply that the positive effect of cross-fostering on piglets born light, did not outweigh its negative effect on piglets born heavy, and also did not contribute to an increase in pre- and post-weaning litter gain. However, more information is needed to confirm our results evaluating the effect of litter mate weight on mortality and subsequent performance of all piglets in the very prolific sows. In addition, a bio economic analysis is necessary to assess what is the best strategy.

Our results furthermore suggest that heavy piglets in UNIFORM litters tried to compensate for their insufficient milk intake by increasing creep feed consumption. This however was not sufficient to overcome their growth disadvantage compared with heavy piglets in MIXED litters. Piglets classified as high consumers were generally the lightest in the week prior to weaning; however, they were able to show catch up growth. Furthermore, being a high consumer pre-weaning, contributed to an improved growth post-weaning.

Chapter 3.

Sow in mid parity are best foster mothers for the pre- and post-weaning performance of both light and heavy piglets.

3.1 Abstract

To improve the performance of lightweight piglets during suckling producers are advised to create uniform litters using young sows. However, fostering piglets to primiparous sows may confer penalties due to their lower milk yield and milk immunoglobulin concentrations compared with multiparous sows. The objective was to determine the effect of foster sow parity (primiparous, second, and mid parity (parity 3 – 5)) on the performance from birth to d 68 of piglets born light (≤ 1.25 kg) or heavy (1.50–2.00 kg) and on creep feed consumption. Piglets (n = 507) considered light or heavy were cross-fostered, creating litters of 13 similar-sized piglets/ litter and were randomly fostered to one of the foster parities. All litters were offered creep feed with a green dye to discern between consumers and non-consumers and the medication administered was recorded. Medication administrated pre- and post-weaning did not differ ($P > 0.05$) across the different experimental groups. A significantly ($P \leq 0.025$) lower number of heavy piglets were removed as a result of pre-weaning weight loss from primiparous and second parity sow reared litters rather than mid parity sow reared litters. The interaction between birth weight × foster parity only affected piglet body weight at d10 ($P = 0.020$); foster parity did not influence body weight of light piglets, but influenced that of heavy piglets. Heavy piglets in primiparous and mid parity sow litters (3.82 and 3.80 kg) were significantly lighter ($P \leq 0.013$) than heavy piglets in second parity sow litters (4.15 kg). As expected, light piglets performed worse pre- and post-weaning than heavy piglets; they were 4.50 kg lighter at d 68. Foster parity significantly affected body weight: primiparous sow reared piglets were weaned lighter ($P = 0.004$) than second parity and mid parity reared piglets (7.52 vs 8.02 kg). Post-weaning (d 68) however, primiparous sow reared piglets achieved similar a body weight as second parity sow reared piglets (29.7 vs. 29.9 kg), whereas mid parity sow reared piglets performed best (31.2 kg, $P \leq 0.079$). Significantly fewer (almost none) of the light than heavy piglets consumed creep feed ($P < 0.001$); significantly ($P = 0.007$) more primiparous and mid parity sow reared piglets were considered consumers than second parity sow reared piglets. The results suggest that irrespectively of birth weight, piglets tend to perform better when in mid parity litters, being weaned heavy and having a high creep feed intake; however, more piglets are removed from such litter pre-weaning. Although second parity sow reared litters were

weaned heavy, they were unable to maintain this body weight advantage post-weaning, due to their low creep feed intake. Primiparous sow reared litters remained small throughout. Long term performance monitoring to slaughter is recommended.

3.2 Introduction

The practice of cross-fostering lightweight piglets, which has resulted from the increased litter size of modern sows, is currently widespread. Creating litter uniformity has been shown to be beneficial for piglets born light with respect to both mortality (Milligan et al., 2001; Deen and Bilkei, 2004) and performance (Douglas et al., 2014c; Huting et al., 2017). However, advice on how to implement this practice is conflicting. For example, AHDB Pork, the body that advises pig farmers in the UK, suggests that light weight piglets should be preferably fostered to young sows, matching the teat size with the small mouths of the piglets (AHDB Pork, 2017a), whereas Genus PIC explicitly advises to avoid using primiparous sows for this purpose (PIC, 2015). These discrepancies might be a result of that one primarily aims to improve the survivability of light piglets while at the same time matches the piglets with sows production potential (AHDB Pork, 2017a; Farmer et al., 2012; 2017), whereas the other might focus more on improving lightweight piglets performance (e.g. PIC, 2015) and may use primiparous sows for heavier piglets to ensure that her teats are sufficiently stimulated for subsequent lactation.

Lightweight piglets have an impaired rooting response (Baxter et al., 2008) and reduced locomotion (Vanden Hole et al., 2018). This will most likely increase their latency time between birth and the first suckle (Tuchscherer et al., 2000; Baxter et al., 2008), and impair their ability to massage and drain the teat efficiently (King et al., 1997; Marshall et al., 2006; Declerck et al., 2017). Differences in teat morphology between primiparous and multiparous sows, suggest that lightweight piglets should be reared by primiparous sows. Teat accessibility in general decreases with increasing parity (Vasdal and Andersen, 2012) and primiparous sows have smaller teats compared with multiparous sows (≥ parity 2) (Balzani et al., 2016b; Ocepek et al., 2016). On the other hand, the milk yield (Beyer et al., 2007; Hansen et al., 2012; Ngo et al., 2012; Strathe et al., 2017) and the immunoglobulin concentration in colostrum and milk from primiparous is lower compared with multiparous sows (≥ parity 2) (Quesnel, 2011; Cabrera et al., 2012; Carney-Hinkle et al., 2013). This may suggest that rearing lightweight piglets on primiparous sows may compromise their pre-weaning performance in a similar manner as for piglets born with an average weight (Bierhals et al., 2011; Miller et al., 2012; Carney-Hinkle et al., 2013).

The primary objectives of this study were to investigate the effect of sow parity on the pre- and post-weaning performance of piglets born light- and heavyweight, and whether sow foster parity has an effect of mortality, the number of medications administered and creep feed consumption. It was hypothesized that whilst the performance of lightweight piglets would benefit from fostering to primiparous sows, the same practice would compromise the performance of litters with heavyweight piglets.

Previous research suggested that heavy piglets tried to compensate for a reduced pre-weaning performance by eating high amounts of creep feed (Huting et al., 2017) though not successful. However, the effectiveness of creep feed consumption on compensatory growth of heavy piglets might be dependent of sow parity and how much milk intake matches their requirements. Therefore, we also aimed to evaluate the effect of foster parity and birth weight on creep feed consumption and teat consistency. Creating litter uniformity has been shown to impair teat consistency during early lactation (Huting et al., 2017), and although teat consistency is normally established during the first 10 days post-partum (Skok and Škorjanc, 2014), variations in sow milking ability may increase competition for the more productive teats also during later lactation. This might especially be the case for piglets reared by primiparous sows and piglets born heavyweight due to their greater growth potential.

3.3 Materials and methods

3.3.1 *Experimental design*

The experiment followed a 2 x 3 factorial design with a minimum of 6 replicates per treatment. The factors considered were piglet birth weight class (light and heavy) and foster parity (primiparous, second and mid parity sows). In accordance with the methodology of Douglas et al. (2014) piglets considered lightweight were those with a birth weight of ≤1.25 kg (minimum 700 g) and piglets considered heavyweight were those with a birth weight between 1.5 and 2.0 kg. Piglets were cross-fostered within the first 24 h post-partum to create litter uniformity (either light or heavy piglets only) and were pseudo-randomly allocated to one of the foster parities (see below). This was done to facilitate light piglet performance and to ensure birth weight will not confound the data. Heavy piglets were used to exacerbate the effect foster parity might have on creep feed consumption and subsequent performance. A power analysis was done using the PROC POWER statement in SAS version 9.4 (SAS inst. Inc. Cary, NC) to determine the required replicates based on the results of previous study (Huting et al., 2017). The experiment was conducted at the Cockle Park Farm Newcastle University (Ulgham, Morpeth, United Kingdom) during 7 consecutive farrowing batches. A total of 507 crossbred piglets (dams were Large White x Landrace and sires were MaxiMus; Rattlerow Farms Limited, Suffolk, UK) were cross-fostered and 39 experimental sows were used. Thirteen litters were cross-fostered to primiparous sows (6 litters of light piglets only and 7 litters of heavy piglets only), 12 litters cross-fostered to second parity sows (6 litters of light piglets only and 6 litters of heavy piglets only), and 14 litters cross-fostered to multiparous sows (6 litters of light piglets only and 8 litters of heavy piglets only). The experiment was approved by the Animal Welfare and Ethics Review Board of Newcastle University (AWERB project ID no. 419) and pigs were maintained in accordance with UK legislation (DEFRA and Red Tractor assurance scheme). Piglets were followed from birth to 10 weeks of age. This project was sponsored by AHDB (Agriculture and Horticulture Development Board) Pork.

3.3.2 *Animals, housing, and management*

The unit operated a 3-week batch system; sows expected to farrow were housed in conventional, partially slatted farrowing crates (237 x 194 cm) on Monday. Sows that had not farrowed by Thursday were induced with a prostaglandin analogue injection (Planate, Intervet UK, Walton, UK). All sows were fed the same home-milled meal (18.5% CP, 9.70 MJ NE/kg diet and 0.95% total lysine) twice a day (0800 h and 1500 h) at an allowance of 1.0 to 2.0 kg/d depending on appetite before farrowing. Once they had farrowed the allowance increased by 0.5 kg/d, based on appetite, until it reached 10 kg/d (at approximately d 21). Water was available *ad libitum* and the temperature of the farrowing unit was maintained at 21 °C throughout lactation.

The average number of piglets born was 13.2 (range 4 to 21) with an average birth weight of 1.39 kg (SD = 0.372), including stillborn and mummies, based on all sows that farrowed over the experimental period in the pig unit. During the first two days of life, piglets were locked into the covered creep area once a day (during morning feeding at 0800 h) to minimize crushing. The creep area was heated with an infrared heat lamp (InterHeat; LPB300S 230v 50-60Hz, 250W) and wood shavings (Goodwills Wood Shavings, Ponteland, Newcastle Upon Tyne, UK) were provided as bedding. All newly born piglets had their teeth clipped within the first 12 h of life. Piglets were tail docked, received an intramuscular iron injection (1 ml; Gleptosil, 200 mg iron/ml, CEVA Animal Health Ltd, Amersham, UK) at approximately 3 days of age and were vaccinated against *Mycoplasma hyopneumoniae* (1 ml; M+PAC, Intervet UK, Walton, UK) at approximately 7 days of age. Piglets had access to a nipple drinker and water trough throughout lactation and *ad libitum* creep feed (diet 1, see below) was provided from 10 days of age onwards. The creep feed provided was supplemented with 1.0 % chromic oxide as indigestible marker (approved by the United Kingdom Food Standards Agency, York, UK).

The day before weaning piglets were vaccinated against *M. hyopneumoniae* (1 ml; M+PAC, Intervet UK, Walton, UK) and porcine circovirus type 2 (1 ml; Ingelvac Mycoflex; Boehringer Ingelheim GmbH, Ingelheim, Germany). After weaning at 28 d of age complete litters were moved to pens (2 x 3 m; one litter/ pen) equipped with multiple nipple drinkers and a multiple-space feeder in a fully slatted purpose-built research facility, where they stayed until approximately 10-weeks of age. Pigs were fed a commercially available four stage pelleted diet, of which the first 3 stages were fed on a kg/pig basis. The first diet was fed until 1 kg was consumed (21.6% CP, 12.3 MJ NE/ kg diet and 1.45% total lysine), the second diet until 2 kg were consumed (21.7% CP, 12.2 MJ NE/kg diet and 1.39% total lysine) and the third diet until 4 kg were consumed (22.3% CP, 12.2 MJ NE/ kg diet and 1.49 % total lysine) per pig. It took the pigs approximately 21 d to consume these 3 diets before moving to the grower feed (22.4 % CP, 12.0 MJ NE/ kg diet and 1.36 % total lysine) which was available *ad libitum* up to 10-weeks of age. The initial room temperature was set at 26 °C and was reduced by approximately 0.2 °C each day until it reached a minimum of 22 °C.

3.3.3 *Experimental procedures*

Within 12 h post-partum piglets were individually weighed to the nearest 1 g. Those that met the birth weight criteria and were free from any physical abnormalities (e.g. splay legs, anaemic) were individually ear tagged to enable identification. Neonates that did not meet these criteria were cross-fostered to non-experimental sows. Piglets were pseudo randomly allocated to one of the three parities: primiparous, second parity or mid-parity sow (parity 3 to 5), whilst balancing for sex and birth parity. Litters of 13 similar sized piglets per sow consisting of only either light or heavy piglets were created within 24 h after post-partum (d 0). The number of light and heavy piglets born/birth parity class that farrowed within 24 h from each other varied considerably, therefore piglets originated from a variety of parities. The majority of piglets were cross-fostered, however, 2-4 piglets remained with their birth sow.

3.3.4 *Pre- and post-weaning performance*

The experimental protocol had well defined intervention points according to established farm practices. Piglets that lost weight during the initial 2 days post-partum, or gained less than 100 g/day during 2 consecutive days from day 3 onwards were removed from the trial and were cross-fostered onto a non-experimental sow. When litter was reduced to below 10 piglets/ sow or a third of the litter lost body weight, the whole litter was taken off trial and was given access to a milk replacer. In addition, the general health of the piglets was examined daily in which piglet posture (i.e. hunched back), breathing (including coughing and sneezing), activity (e.g.

mobility, lameness, responsiveness), and faecal consistency was assessed and any interventions were monitored and recorded. Medication administered for scour, swine dysentery and lameness were Norodine (Norodine 24, Norbrook, Corby, UK), Denagard (Novartis Animal Health, Grimsby, UK) and a 50:50 mixture of Pen & Strep (Pen & Strep, Norbrook, Corby, UK) and Tolfine (Tolfine, Vetoquinol, Paulerspury, Towcester, UK) respectively with the dose depending on the size of the pig. If more than 3 piglets in a litter were diagnosed with diarrhoea the whole litter was treated.

All piglets were weighed at 10 days of age, the point at which creep feed was provided *ad libitum* up to weaning. A feed hopper with 2 feeding spaces and additional tray covering the slats to ensure any spillage was collected was fixed to the wooden board of the pen close to the creep area. The amount of creep feed offered and refused was measured on a daily basis (0800 h).

Piglets were individually weighed at weaning and once every week (Wednesday), up to 10-weeks of age. At the same time the amount of feed offered and refused per pen was recorded to estimate weekly feed intake. At approximately 10-weeks of age the pigs were returned to the commercial pig unit.

3.3.5 *Teat position and teat consistency*

The teat position of each individual piglet was recorded using the teat pair locations 1 to 7, from anterior to posterior, during 4 successful suckling bouts at d 12 - 13 of lactation. A suckling bout started when more than half of the litter gathered at the sow udder and began massaging, and ended when more than half of the piglets fell asleep at the udder, left the udder, or when the sow changed position (in accordance with Douglas et al., 2014; Huting et al., 2017). The preferred teat pair of each individual was classified into one of the three groups: anterior (teat pair 1 and 2), middle (teat pair 3 to 5) or posterior (teat pair ≥ 6) teat pair. A piglet was given a consistency score (Ci) of 1 when it used the same teat during a suckling bout. The Ci score was used to calculate the consistency score of the entire litter by expressing the number of piglets that scored 1 relatively to the total number of piglets within the litter.

3.3.6 *Individual creep feed intake*

Individual creep feed intake was accessed in two ways: 1) by the subjective observation of visibly green faeces (dye present) and 2) objectively, measuring colour by using a colour reader (Huting et al., 2017). Creep feed consumption in our farm does not start before d 19 (e.g. Huting et al., 2017), therefore, faecal samples were collected on days 19, 21 and 25, by placing the individual piglet on a weighing scale for a maximum of 4 minutes, stimulating voluntary defecation; samples with watery faeces were excluded from the analysis. Piglets were classed into four different consumer classes (i.e. non, low, moderate and high) depending on the number of faecal samples that appeared to be visually green (Huting et al., 2017) and faecal samples were accessed using the CIELAB colour space (Color reader CR-10, Konica Minolta Sensing Inc., Sunderland, UK) following the methodology of (Huting et al., 2017). Faecal colour was expressed in three different coordinates including L* (dark - light), a* (green – red) and b* (blue – yellow). Chromaticity coordinate a*, which when negative indicates greener faeces, and hue angle (H*), which defines how the colour is perceived and could be calculated from a* and b*, were of interest. It has been shown preciously that faeces becomes greener as pigs mature (Huting et al., 2017) therefore faecal samples from two non-experimental litters (6 piglets/ litter) of the same batch were taken. These piglets were sampled on the same day as the experimental piglets and were spray marked with different combinations of marks to ensure the same piglets were sampled during all sampling days. The latter was used to correct the obtained estimates for experimental day resulting in adjusted a* and adjusted H* (see for detailed methodology Huting et al. (2017). The lower the adjusted a* and the greater the adjusted H*ab, the greener the faeces.

3.3.7 *Statistical analysis*

Two litters, one primiparous sow and one mid parity sow, both consisting of light piglets only were removed from trial as their litter sizes became less than 10 piglets/sow. In addition, during one farrowing batch no second parity sows were available. A chi-square test was carried out to test: 1) whether the reason for removal (e.g. mortality, sickness, weight loss) and 2) the quantity of medication administered were affected by birth weight class and foster parity.

The PROC MIXED procedure in SAS version 9.4 (SAS inst. Inc. Cary, NC) was used to analyse the pre- and post-weaning performance data. Two different PROC MIXED models were run. Firstly, litter mean was the experimental unit for accessing pre- and post-weaning performance. Litter size was adjusted for the removal of piglets (litter size = [(Σ all the piglet hours piglets were suckling)/ 24 h]/ total period in d) and was added to all models as a covariate. Likewise, the average pre- and post-weaning feed intake was adjusted to the number of animals that resided with their foster sow or within the pen (FI (g/(day · piglet) = [(total amount consumed in g)/ total time (h) piglets spent with their foster sow/ within pen] x 24 h). Secondly, the experimental unit for the effect of teat pair class and consumer class on pre- and post-weaning performance was piglet nested within litter and litter nested within farrowing batch. Main effects of interest for all mixed models were birth weight class, foster parity and their interaction. Individual models were run for the different days. Due to the low number of maternally raised piglets/ litter (i.e. 2-4 piglets/ litter) cross-fostering or not, was not included in the final model. Furthermore, because birth parity could not be equally distributed within and between litters, also birth parity was not included in the final model. Additional main effects of interest for the second model were teat pair class or consumer class and their interactions with birth weight class and foster parity. Because the number of consumers per birth weight class and foster parity were unbalanced, the interactions between consumer class × birth weight class and consumer class × foster parity were excluded from the final model. Sex did not significantly affect pre- and post-weaning performance nor did it interact with any of the other variables and was therefore omitted from subsequent analysis. All data were blocked by farrowing batch. Several covariance structures (i.e. first-order auto regression, compound symmetry and variance components) were tested for the RANDOM effects, and the variance components was selected as it resulted in the lowest Akaike information criteria. The residual variance of the data were tested for normality using the UNIVARIATE procedure of SAS. Graphical diagnostics and the Levene's test (HOVTEST) in PROC GLM was used to test whether the population variances were equal. When data were unbalanced, the denominator degrees-of-freedom (DDF) Satterthwaite was used for adjusting the degrees of freedom to unequal variance and studentized maximum modulus (SMM) using a Bonferroni correction (BON) was used for multiple comparisons; in all other cases protected difference (PDIFF) was used to compare means. Data were expressed as least square means (LSM) with approximate standard errors of the differences of means (SED) unless stated otherwise. Differences were considered significant at 5% and reported as tendencies at 10%..

Two different logistic regressions (PROC LOGISTIC) were conducted to: 1) identify whether piglet likelihood to become a non-consumer or consumer (i.e. low, moderate and high consumer) was under the influence of birth weight class, foster parity and their interaction with litter as experimental unit and 2) whether this was under the influence of teat pair class with piglet as experimental unit. For the first logistic regression a binomial model (Y/*n*) was used with the sum of piglets belonging to one of the consumer classes (Y) expressed against the total number of piglets in the litter (*n*). In the second logistic regression, teat pair class was added to determine whether piglet likelihood to become non-consumer or consumer was influenced by teat pair. The response variable of interest (i.e. consumer class) had more than two levels and was therefore formatted to estimate piglet probability to end up in one of the intermediate consumer classes (low or moderate class), with zero representing everything other than the consumer class of interest. The DESCENDING option was used to ensure the likelihood to end up in the 'highest' consumer class was tested.

The Pearson correlation coefficient (r) was used to investigate whether creep feed intake was correlated with adjusted a* and adjusted H*ab, and whether colour reader measurements and post-weaning performance were correlated.

3.4 Results

A total of 132 piglets (26.0%) remained with their birth sow; the remaining 375 piglets were cross-fostered. Mid parity sows had an average parity of 3.57 (SD = 0.756). As expected, litter CV after cross-fostering (d 0) was significantly ($P < 0.001$) greater in light than heavy litters (14.1, SD = 2.9 vs. 8.24, SD = 3.03), but was neither different between foster parities nor was it affected by the interaction between birth weight class × foster parity ($P > 0.05$).

Although cross-fostering created litters of 13 piglets/ sow, litter size decreased over time. Litter size at weaning (d 28.6, SD = 0.5) was significantly ($P = 0.009$) lower for light (11.6, SD = 0.9) than heavy litters (12.3, SD = 0.9). Primiparous and second parity sows weaned on average 12.3 (SD = 0.9) and 12.1 (SD = 0.9) piglets respectively whereas mid parity sows weaned on average 11.5 (SD = 0.9) piglets ($P = 0.063$).

Table 3.1 shows the total number of pigs allocated and the number of pigs removed or treated. Pre-weaning mortality (i.e. < 2 d of age and d 2 to weaning) was significantly ($P \leq 0.034$) different between the different treatments. Irrespective of foster parity, piglets born light had a greater mortality rate (5.6%) when compared with heavy piglets (0.4%) during the initial first 2 days post-partum. Pre-weaning removal rate as result of weight loss was significantly ($P = 0.020$) different across the different groups, with parity class affecting the number of light and heavy piglets removed. For light piglets this manifested only as a tendency ($P = 0.086$), whereas heavy piglets reared by primiparous and second parity sows had a significant ($P \leq 0.025$) lower pre-weaning removal rate compared with similar sized piglets reared by mid parity sows.

The number of pre-weaning medication administered was not affected ($P > 0.05$) by birth weight class, foster parity or their interaction. However, the interaction between foster parity × birth weight class ($P \leq 0.013$) affected the number of medications administered for scour and 'other' (i.e. meningitis, pneumonia) post-weaning. A significantly ($P < 0.001$) lower number of

Table 3.1 The total number of pigs allocated and the number of pigs removed or treated, with the reason for their removal and treatment, according to foster parity and birth weight class. Light (less than 1.25 kg) or heavy (1.50 – 2.00 kg) piglets were fostered on a primiparous, second, or mid parity sows (parity 3 – 5). The number of pigs removed are expressed in absolute values and relative (%) to the total number of pigs.[1]

Foster sow parity class	Primiparous		Second		Mid			
Birth weight class	Light	Heavy	Light	Heavy	Light	Heavy	Total	Significance[2]
Number of pigs on trial								
d 0	78	91	78	78	78	104	507	0.136
d 10	71	90	74	75	72	94	476	0.183
d 28	70	90	70	75	68	93	466	0.096
d 68	69	89	70	73	68	92	461	0.107
Number of pigs removed								
Found dead at < 2 d of age	4 (5.1%)	0 (0.0%)	1 (1.3%)	0 (0.0%)	2 (2.6%)	0 (0.0%)	7 (1.4%)	0.027
Found dead at > 2 to < 28 d of age	2 (2.6%)	0 (0.0%)	0 (0.0%)	1 (1.3%)	4 (5.1%)	0 (0.0%)	7 (1.4%)	0.034
Lost weight pre-weaning	2^{B} (2.6%)	1^{b} (1.1%)	7^{A} (9.0%)	2^{b} (2.6%)	4^{AB} (5.1%)	11^{a} (10.6%)	27 (5.3%)	0.020
Post-weaning mortality; > 28	1 (1.4%)	1 (1.1%)	0 (0.0%)	2 (2.7%)	0 (0.0%)	1 (1.08%)	5 (1.1%)	-
Total	9 (11.5%)	2 (2.2%)	8 (10.3%)	5 (6.4%)	10 (12.8%)	12 (11.5%)	46 (9.1%)	0.122
Number of pigs treated								
Pre-weaning								
Lameness	12 (15.4%)	12 (13.2%)	13 (16.7%)	15 (19.2%)	9 (11.5%)	10 (9.6%)	71 (14.0%)	0.485
Scour[3]	14 (17.9%)	13 (14.3%)	7 (9.0%)	11 (14.1%)	7 (9.0%)	10 (9.6%)	62 (12.2%)	0.393
Other[4]	2 (2.6%)	2 (2.2%)	1 (1.3%)	0 (0.0%)	1 (1.3%)	1 (1.0%)	7 (1.4%)	0.779
Total	28 (35.9%)	27 (29.7%)	21 (26.9%)	26 (33.3%)	17 (21.8%)	21 (20.2%)	140 (27.6%)	0.241
Post-weaning								
Lameness	4 (5.7%)	3 (3.3%)	2 (2.9%)	5 (6.7%)	4 (5.9%)	6 (6.5%)	24 (5.2%)	0.827
Scour[3]	0^{b} (0.0%)	3 (3.3%)	1^{b} (1.4%)	4 (5.3%)	9^{a} (13.2%)	6 (6.5%)	23 (5.2%)	0.002
Other[4]	8^{a} (11.4%)	9^{aA} (10.0%)	10^{a} (14.3%)	11^{a} (14.7%)	1^{b} (1.8%)	3^{bB} (3.2%)	42 (9.0%)	0.013
Total[6]	12 (17.1%)	15 (16.7%)	13 (18.6%)	20 (26.7%)	14 (20.5%)	15 (16.1%)	89 (19.1%)	0.558

[1] Pigs were cross fostered within 12 - 24 h after birth (d 0) in litters of 13 piglets/ litter and creep feed was provided from 10 days to weaning (d 28.6, SD = 0.5). Pigs remained in the same litter until approximately 10 weeks of age (d 67.6, SD = 0.5). During one farrowing batch no second parity sows were available. In addition, one primiparous and one mid parity sow litter consisting of light piglets were removed from trial as litter size came < 10 piglets/litter.

[2] Data were analyzed with a chi-square test. Absence of statistics indicates there were insufficient observations for a chi-square test. Numbers within row and within birth weight class with different superscript tended ($P < 0.10$, ^{A,B}) or differed statistically ($P < 0.05$, ^{a,b,c}).

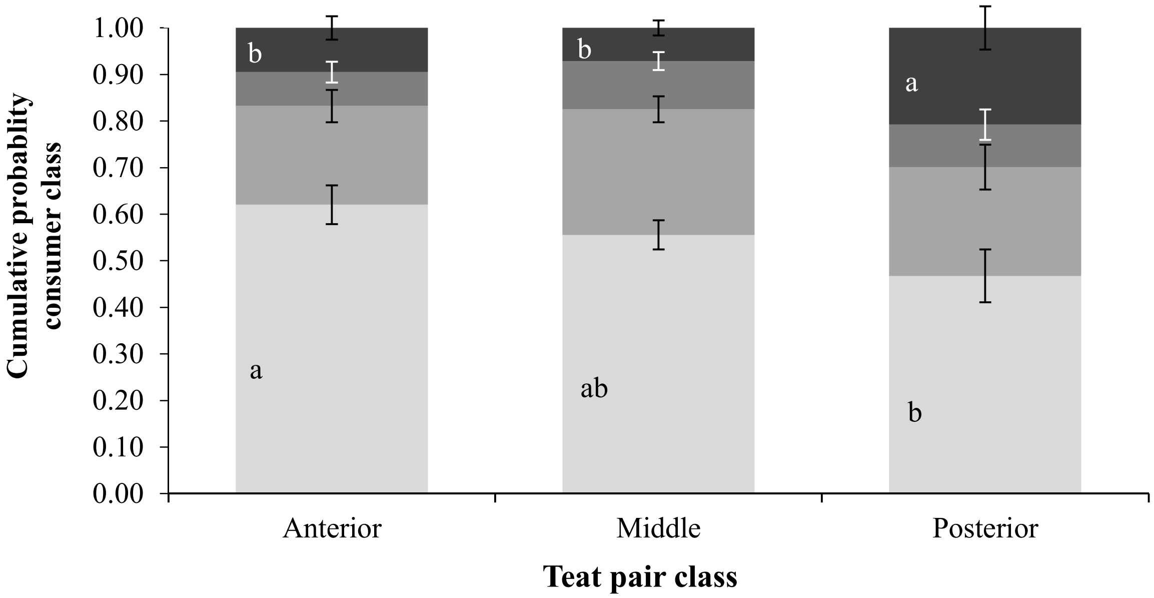
[3] The values only includes piglets that were treated for scour after being diagnosed with diarrhea and not piglets that were treated as a result of more than 3 piglets in the litter having diarrhea.

[4] Piglets treated for meningitis or pneumonia

light piglets reared by primiparous and second parity sows were treated for scour, compared with similar sized piglets reared by mid parity sows. No differences were seen for heavy piglets across the different foster sow parities. Medication administered for 'other' on the other hand was significantly ($P < 0.001$) greater for primiparous and second parity sows reared light piglets when compared with mid parity sows reared light piglets. Similar results were seen for heavy piglets with heavy piglets reared by second sows had a significant ($P = 0.008$) greater number of heavy piglets treated for 'other' compared with heavy piglets reared by mid parity sows; only a tendency ($P = 0.064$) was observed between primiparous sows and multiparous sows reared heavy piglets.

3.4.1 *Teat position and teat consistency*

Teat C_i (i.e. using the same teat during a suckling bout) as expressed relatively to the number of piglets within litter averaged 92.8% (SD = 10.71) and was not significantly ($P > 0.05$) affected by birth weight class, foster parity or their interaction.



Consumer class	**Non**	**Low**	**Moderate**	**High**
Significance				
Teat pair class	0.094	0.429	0.619	0.004

Figure 3.1 The effect of piglet preferred teat pair on piglets probability to be classified non-consumer or consumer. Piglets were classified as either non-consumers or consumers (low, moderate, or high) on the basis of the number of positive faecal samples. Teat pair class was classified according to anatomical location of the teats (i.e. anterior [teat pair 1-2], middle [teat pair 3-5], or posterior [teat pair ≥ 6]). Data are represented in probability ± SE. Within consumer class bars with different superscripts ([a,b]) differ significantly ($P < 0.05$) across the different teat pair classes.

The effect of piglet preferred teat pair on piglet cumulative probability to become non-consumer or consumer (i.e. low, moderate and high) is shown in Figure 3.1. Piglets suckling the anterior and middle teat pair were less likely ($P \leq 0.024$) to be considered high-consumer (0.095, SD = 0.025 and 0.071, SD = 0.016 respectively) compared with piglets suckling the posterior teat pair (0.208, SD = 0.046).

Teat position. Table 3.2 shows the effect of foster parity and preferred teat pair class on piglet performance from birth to 10 weeks of age. The interaction between birth weight class × teat pair class did not influence pre- and post-weaning performance and the interaction between teat pair class × foster parity only tended to influence body weight at d 28 ($P = 0.089$). At weaning primiparous sow reared piglets suckling the anterior teat pair only tended to be ($P = 0.074$) heavier compared with primiparous sow reared piglets suckling the posterior teat pair, whereas for second and mid parity sow reared piglets both piglets suckling the middle or posterior teat pair were weaned significantly ($P \leq 0.011$) lighter than piglets suckling the anterior teat pair.

Teat pair class significantly ($P < 0.001$) affected pre-and post-weaning performance. On d 28 piglets suckling the anterior teat pair were significantly ($P \leq 0.020$) heavier (8.37 kg, SD = 1.37) than piglets suckling the middle teat pair (7.76 kg, SD = 1.61); piglets suckling the posterior teat pair were the lightest (7.39 kg, SD = 1.25). Similar results were seen for ADG between birth and weaning ($P < 0.001$) with piglets suckling the anterior teat pair having the highest ADG (243 g/d/piglet, SD = 44.9), followed by piglets suckling the middle teat pair (223 g/d/piglet, SD = 52.1); piglets suckling the posterior teat pair had the lowest pre-weaning ADG (211 g/d/piglet, SD = 41.1). Only a tendency was sustained post-weaning with piglets suckling the anterior teat pair being > 500 g ($P \leq 0.082$) heavier at 10 weeks of age than piglets suckling the mid and posterior teat pair class.

3.4.2 *Creep feed consumption*

Litter level. Most (> 80%) creep feed was consumed during the last week before weaning (d 21 - 28) with half of the total amount consumed (50%) being eaten during the last 3 days before weaning (> d 25). The effect of foster parity and birth weight class on creep feed consumption is shown in Figure 3.2. Neither foster parity nor the interaction between birth weight class × foster parity significantly affected creep feed intake ($P > 0.05$). However, creep feed consumption was significantly ($P < 0.001$) affected by birth weight class, with light piglets consuming less (65.9 g/piglet, SD = 195) than heavy piglets (261 g/piglet, SD = 207).

Table 3.2 The effect of foster sow parity (primiparous, second or mid parity sow [parity 3-5]) and piglet preferred teat pair class on performance from birth to 10 weeks of age.[1]

Foster sow parity class	Primiparous			Second			Mid				Significance[2]		
Teat position	Anterior	Middle	Posterior	Anterior	Middle	Posterior	Anterior	Middle	Posterior	SED	Teat pair class	Birth weight × Teat pair class	Foster parity × Teat pair class
Number of piglets													
d 28	44	88	28	45	77	23	48	87	26				
d 68	43	87	28	43	77	23	47	87	26				
Body weight, kg													
d 0	1.36	1.39	1.34	1.41	1.38	1.37	1.41	1.39	1.37	0.012	0.323	0.111	0.467
d 28	7.69[A]	7.51	6.92[B]	8.50[a]	7.73[b]	7.54[b]	8.90[a]	8.03[b]	7.70[b]	0.113	<0.001	0.783	0.089
d 34	9.27	8.96	8.40	9.64	9.03	8.85	10.3	9.56	9.29	0.123	<0.001	0.625	0.644
d 68	30.3	29.8	28.6	30.3	29.5	30.1	32.1	30.9	30.8	0.331	0.032	0.684	0.507
Average daily gain, g/ day													
d 0 - 28	222	215	196	248	224	217	260	231	220	3.70	<0.001	0.813	0.122
d 28 - 34	263	243	244	191	216	218	234	255	265	12.4	0.566	0.657	0.270
d 28 - 68	579	572	555	560	559	579	594	586	593	7.38	0.774	0.719	0.538

Within foster parity estimates within row with different superscripts differ significantly ([a,b] $P < 0.05$).
[1] Teat pair class was classified according to anatomical location of the teats (i.e. anterior [teat pair 1-2], middle [teat pair 3-5], or posterior [teat pair ≥ 6]) and was assessed at d 12 of age. Pigs were cross-fostered within 12 - 24 h after birth (d 0), creep feed was provided from 10 days to weaning (d 28.6, SD = 0.46) and piglets remained in the same litter until approximately 10 weeks of age (d 67.6, SD = 0.46). Individual pigs were weighed at birth (within 12 h after birth), d 28, 1 week post-weaning and at 10 weeks of age.
[2] In addition to the significant effect shown here, birth weight class affected ($P < 0.05$) all performance parameters. Also foster parity class significantly ($P < 0.05$) affected body weight at d 28, d 34 and d 68.

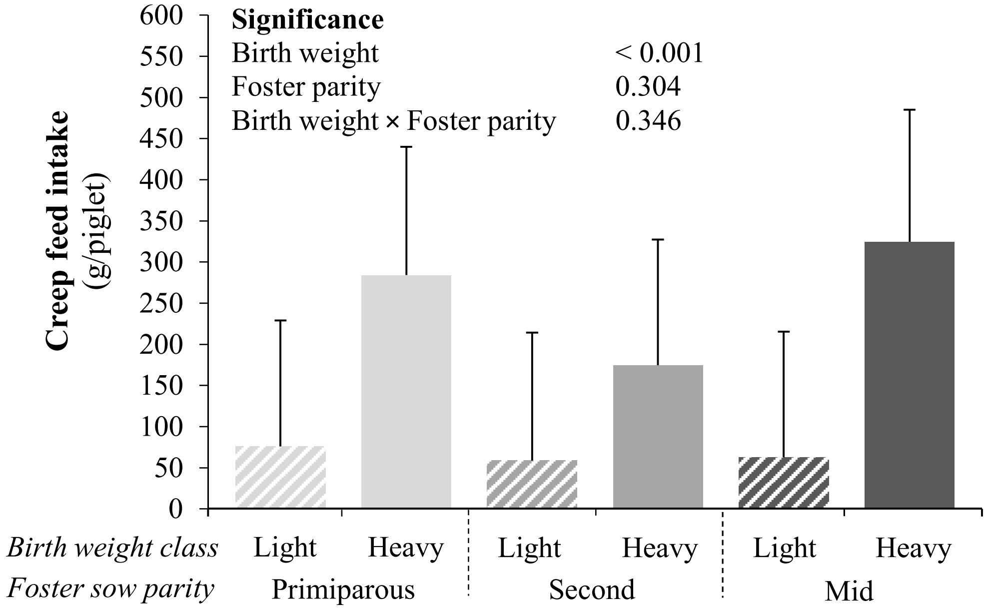
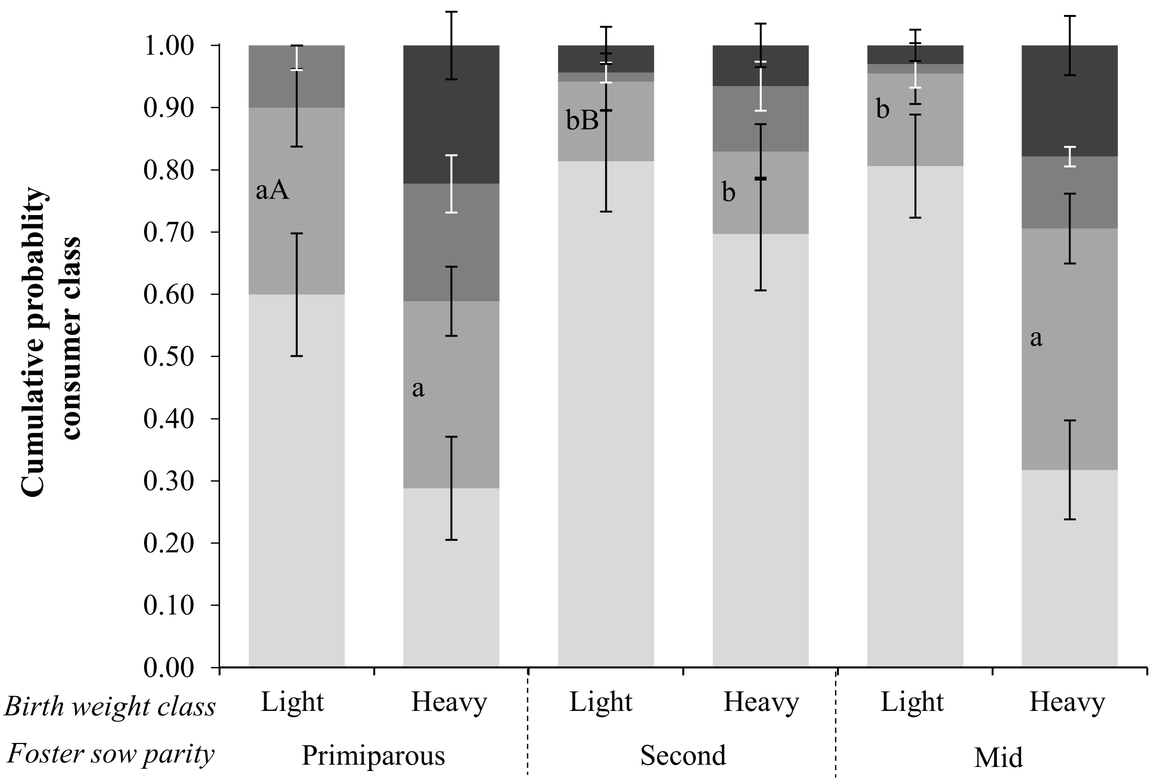


Figure 3.2 The effect foster sow parity (primiparous, second, or mid parity sow [parity 3 – 5]) and birth weight class (light [≤ 1.25 kg] or heavy [1.50 – 2.00 kg]) on creep feed consumption (g/ piglet ± SD).

Individual piglet. Figure 3.3 illustrates the effect of foster parity and birth weight class on the cumulative probability of consumer class (i.e. non-, low, moderate and high consumer). The interaction between birth weight class × foster parity only tended (P = 0.059) to influence the probability to become low consumers.

Birth weight class significantly influenced the probability of being classified as non-consumer or consumer. In general light piglets had a greater likelihood to be classified as non-consumers (0.740, [95% confidence interval 0.737, 0.743]) compared with heavy piglets (0.435, [0.431, 0.438]) and a lower likelihood to be classified as consumers, irrespectively of consumer class. In addition, foster parity influenced the likelihood for becoming non-consumer (P = 0.007), low- (P = 0.008) and moderate consumer (P = 0.027). In general, primiparous and mid parity sow reared piglets had a lower likelihood to become non-consumers and a greater likelihood to become low consumers compared with second parity sow reared piglets. The likelihood to be classified as moderate consumer was significantly ($P \leq$ 0.044) greater for primiparous sow reared piglets (0.139, [0.137, 0.141]) compared with second and mid parity sow reared piglets (0.040, [0.039, 0.042] and 0.043, [0.041, 0.044] respectively).

Table 3.3 shows the effect of consumer class on piglet performance from birth to 10 weeks of age. Consumer class significantly affected body weight at d 19 (P < 0.001), at the start of faecal sampling, weaning (P = 0.039), and at 10 weeks of age (P = 0.020). Non- and low consumers were significantly ($P \leq$ 0.040) heavier at d 19 and weaning compared with high consumers, whereas at 10 weeks of age, non-consumers were significantly ($P \leq 0.044$) lighter than moderate consumers. Furthermore, pre- and post-weaning ADG were significantly ($P \leq 0.037$) affected by consumer class. Although, high consumers gained significantly less ($P \leq 0.027$) between birth and d 19 and birth and weaning than for instance non- consumers, they gained significantly ($P \leq 0.044$) more during the post-weaning period (between weaning and 10 weeks of age) compared with non-consumers.



Consumer class	Non	Low	Moderate	High
Significance				
Birth weight	<0.001	0.087	0.004	<0.001
Foster	0.007	0.008	0.027	0.130
Birth weight × Foster	0.248	0.059	0.357	0.497

Figure 3.3 The effect foster sow parity (primiparous, second, or mid parity sow [parity 3 – 5]) and birth weight class (light [≤ 1.25 kg] or heavy [1.50 – 2.00 kg]) on the cumulative probability of consumer class. Data are represented in probability ± SE. The comparison for the effect of foster parity on consumer class was made within birth weight class with the different superscripts either differ significantly (^{a,b,c} $P < 0.05$) or tended (^{A,B} $P < 0.10$) to differ.

The correlations ($P < 0.05$) between the colour readings (i.e. adjusted a* and adjusted H*ab) for the different sampling days (i.e. d 19, d 21 and d 25) and ADG between weaning and d 34 were generally weak (r = < +/- 0.40), as illustrated in Figure 3.4 and Figure 3.5 for adjusted a* and adjusted H*ab respectively. Negative correlations between adjusted a* and ADG were found, whereas adjusted H*ab was positively correlated with ADG. Similar results were found between weaning and 10 weeks of age.

Table 3.3 The effect of consumer class on pre- and post-weaning performance. Piglets were classified as either non-consumers or consumers (low, moderate, or high) on the basis of the number of positive faecal samples (dye present) during the different sampling days (i.e. d 19, 21, and 25).[1]

Consumer class	Non consumer	Low consumer	Moderate consumer	High consumer	SED	Significance[2]
Number of piglets						
d 28	261	115	43	47		
d 68	257	115	43	46		
Body weight, kg						
d 0	1.34	1.39	1.44	1.39	0.005	0.508
d 19	5.90^{a}	5.79^{a}	5.57^{aA}	5.12^{bB}	0.033	<0.001
d 28	7.90^{a}	7.92^{a}	7.78^{ab}	7.33^{b}	0.046	0.039
d 34	9.19	9.43	9.59	9.05	0.050	0.126
d 68	29.8^{b}	30.8^{ab}	31.6^{a}	30.8^{ab}	0.136	0.020
Average daily gain, g/day						
d 0 - 19	229^{a}	223^{a}	209^{ab}	190^{b}	1.58	<0.001
d 0 - 28	228^{a}	228^{a}	222^{ab}	209^{b}	1.51	0.031
d 19 - 28	227	240	249	249	2.30	0.037
d 28 - 34	217^{b}	253^{a}	294^{a}	276^{a}	4.24	0.001
d 28 - 68	563^{bB}	583^{aA}	609^{a}	608^{a}	2.78	0.001

[1] Data are expressed at least square means. Averages within row with different superscripts (^{a,b,c}) differ significantly (P < 0.05) or tended (^{A,B}) to differ (P < 0.10).
[2] In addition to the consumer class effect shown here, birth weight class affected (P < 0.05) all performance parameters except for ADG between d 19 – 28. Also foster parity class significantly (P < 0.05) affected body weight at d 19, d 28, d 34, and d 68, ADG between d 19 – 28, d 0 and 28, and d 28 - 68.

3.4.3 *Pre- and post-weaning performance*

The relative weight and P2 back fat loss (weight/ P2 back fat loss in % = [(parameter post-partum – parameter at weaning)*100]/ parameter post-partum) of the foster sow was not different across treatments (P > 0.05 for birth weight, foster parity, and their interaction) and was on average 14.3% (SD = 10.3) and 25.2% (SD = 14.0) respectively. Table 3.4 shows the effect of foster parity, birth weight class and their interaction on piglet performance from birth to 10 weeks of age.

Performance at d 10. A significant interaction between birth weight class × foster parity was found for body weight at d 10 (P = 0.020). Although, foster parity did not influence body weight of light piglets, it influenced the performance of heavy piglets. Primiparous and mid parity sow reared heavy piglets were significantly ($P \leq 0.013$) lighter than second parity sow reared heavy piglets. In addition, birth weight class (P < 0.001), but not foster parity (P > 0.05), influenced body weight at d 10.

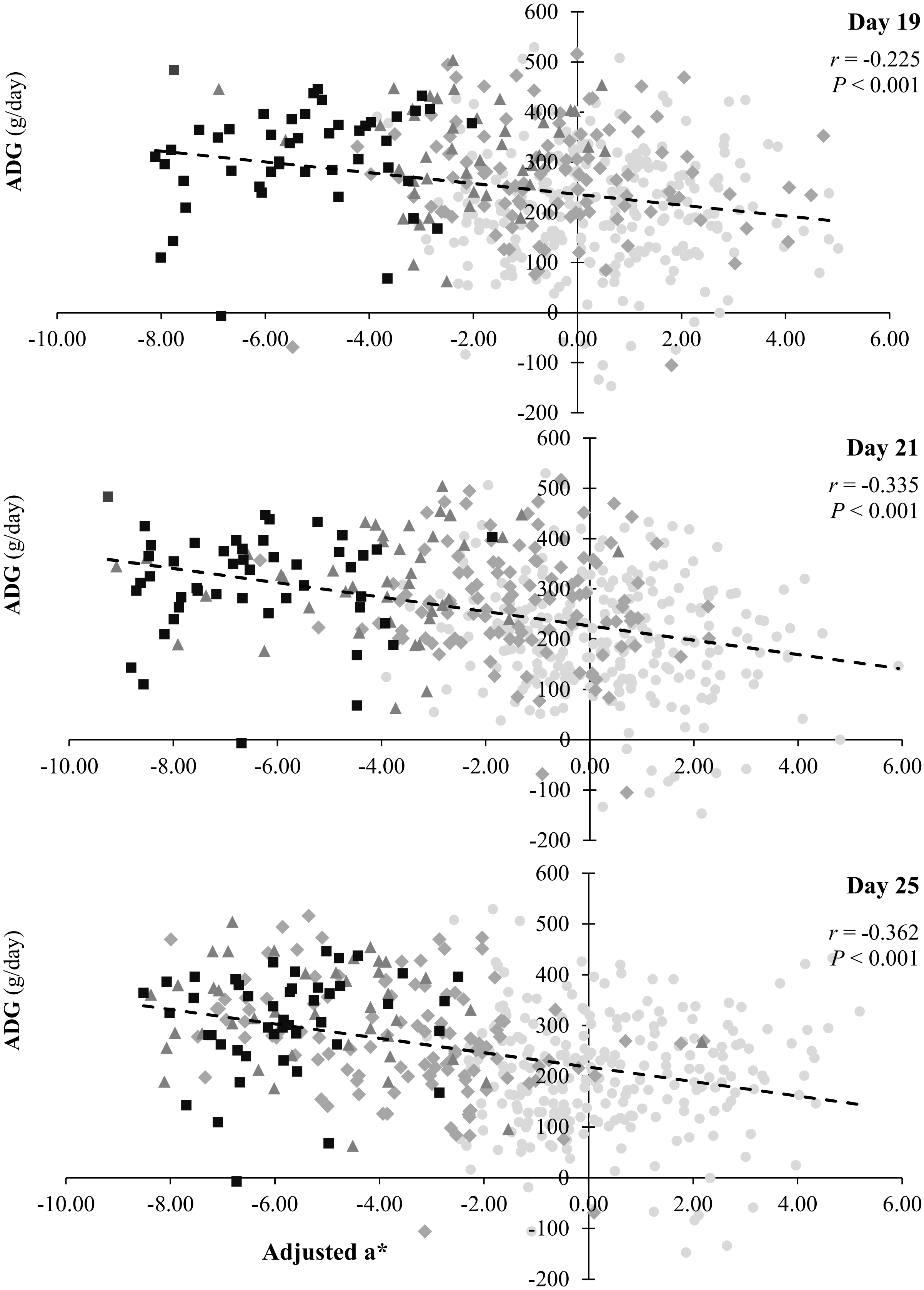


Figure 3.4 Correlation between adjusted a* measured at d 19, d 21 and d 25 and post-weaning ADG (g/day) between weaning and one week post-weaning (d 34). The different colours/ markers represent ● non-consumer, ♦ low, ▲ moderate, and ■ high consumer

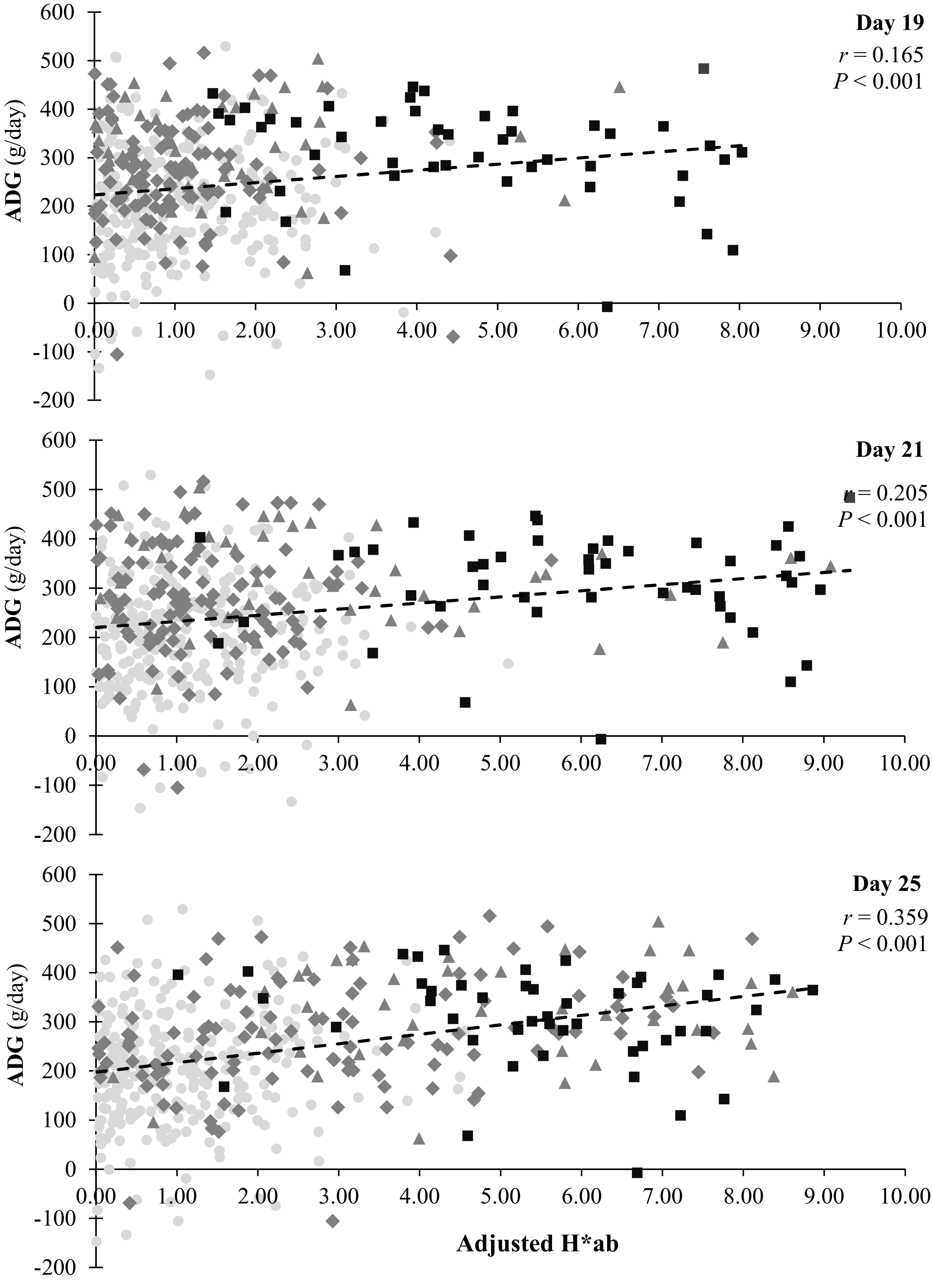


Figure 3.5 Correlation between adjusted H*ab measured at d 19, d 21 and d 25 and post-weaning ADG (g/day) between weaning and one week post-weaning (d 34). The different colours/ markers represent ● non-consumer, ♦ low, ▲ moderate, and ■ high consumer

Table 3.4 The effect of foster sow parity (primiparous, second or mid parity sow [parity 3-5]) and birth weight class (light [less than 1.25 kg] or heavy [1.50 – 2.00 kg]) and their interaction on performance from birth to 10 weeks of age.[1,2]

Foster sow parity class	Primiparous		Second		Mid			Significance		
Birth weight class	Light	Heavy	Light	Heavy	Light	Heavy	SED	Birth weight class	Foster parity	Birth weight × Foster parity
Body weight, kg										
d 0	1.06	1.68	1.04	1.71	1.07	1.69	0.013	<0.001	0.828	0.059
d 10	2.94[c]	3.82[b]	2.88[c]	4.15[a]	3.08[c]	3.80[b]	0.094	<0.001	0.403	0.020
d 28	6.88	8.16	7.25	8.80	7.43	8.70	0.195	<0.001	0.004	0.664
d 34	8.29	9.67	8.40	10.0	8.69	10.7	0.216	<0.001	0.011	0.356
d 68	27.8	31.6	27.8	32.0	28.4	33.9	3.73	<0.001	0.025	0.269
Average daily gain, g/day										
d 0 - 10	173[c]	197[bd]	171[cd]	227[a]	186[c]	196[b]	8.45	<0.001	0.225	0.025
d 0 - 28	204	226	217	248	221	245	6.26	<0.001	0.007	0.738
d 10 - 28	224	246	239	261	240	273	9.19	<0.001	0.022	0.681
d 28 - 34	227	249	199	203	209	327	24.9	0.057	0.066	0.088
d 28 - 68	535	602	527	596	538	646	12.7	<0.001	0.039	0.145
Feed intake, g/ day/ piglet										
d 28 - 34	197	234	174	182	179	271	17.5	0.006	0.034	0.073
d 28 - 68	649	731	657	725	664	818	21.6	<0.001	0.028	0.073
Feed intake, kg/ piglet										
d 28 - 34	1.18	1.41	1.04	1.09	1.08	1.63	0.105	0.006	0.034	0.073
d 28 - 68	25.3	28.5	25.6	28.3	25.9	31.9	0.841	<0.001	0.028	0.073
Gain to feed ratio										
d 28 - 68	0.824	0.825	0.803	0.826	0.812	0.789	0.077	0.961	0.065	0.065
Total litter CV										
d 28	14.4	10.6	15.9	11.2	13.8	13.8	1.39	0.029	0.613	0.226
d 68	11.8	10.2	11.3	9.77	12.5	10.4	1.19	0.079	0.741	0.967
Total litter weight, kg										
d 28	83.4	98.5	84.6	106	87.6	103	2.30	<0.001	0.081	0.278
d 68	329	374	328	378	337	400	7.217	<0.001	0.036	0.372

[1] Pigs were cross-fostered within 12 - 24 h after birth (d 0), creep feed was provided from 10 days to weaning (d 28.6, SD = 0.46) and piglets remained in the same litter until approximately 10 weeks of age (d 67.6, SD = 0.46). Individual pigs were weighed at birth (within 12 h after birth), d 10, 19, 28, 1 week post-weaning and at 10 weeks of age.

[2] Data are expressed at least square means. Averages within row with different superscripts ([a,b,c,d]) differ significantly ($P < 0.05$).

Performance at weaning. Body weight, total litter weight and litter CV at weaning were not significantly affected by the interaction between birth weight class × foster parity ($P < 0.05$). However, birth weight class ($P < 0.001$ and $P < 0.001$ respectively) and foster parity ($P = 0.004$ and $P = 0.081$ respectively) influenced weaning weight and total litter weight at weaning. Litter CV at weaning was only influenced by birth weight ($P = 0.029$). Piglets born light were lighter at weaning (7.19 kg, SD = 0.59 vs. 8.55 kg, SD = 0.66), had a greater litter CV (14.7, SD = 3.7 vs. 11.9, SD = 3.7) and a lower total litter weight (85.2 kg, SD = 6.5 vs. 103 kg, SD = 7) compared with heavy piglets. On the other hand, primiparous sow reared piglets were weaned 500 g lighter (7.52 kg, SD = 0.56) when compared with piglets reared by second and mid parity sows (8.02 kg, SD = 0.56 and 8.02 kg, SD = 0.60 respectively). A similar effect of foster parity was found for total litter weight at weaning with primiparous reared piglets having a lower total litter weight (91.0 kg, SD = 6.20) when compared with piglets reared by second and mid parity sows (95.5 kg, SD = 6.18 and 95.5 kg, SD = 6.53 respectively).

Performance at 1 week post-weaning. Only birth weight class ($P < 0.001$) and foster parity ($P = 0.011$) influenced piglet body weight at 1 week post-weaning; the same was the case for feed intake between weaning and d 34 ($P = 0.006$ and $P = 0.034$ respectively). Lightweight piglets were 1.6 kg lighter at 1-week post-weaning (8.46 kg, SD = 0.63 vs. 10.1 kg, SD = 0.7) and ate less during the immediate post-weaning period (183 g/d/piglet, SD = 46 vs. 229 g/d/piglet, SD = 46) compared with heavy piglets. Post-weaning primiparous sow (8.98 kg, SD = 0.595) reared piglets were significantly lighter at d 34 ($P = 0.041$) when compared with piglets reared by mid parity sows (9.67 kg, SD = 0.629). On the other hand, second parity sow reared piglets ate less (178 g/d/piglet, SD = 44.9) between weaning and d 34 ($P = 0.044$) when compared with piglets reared by mid parity sows (225 g/d/piglet, SD = 46.7). No significant ($P = 0.066$) differences were observed for ADG between weaning and 1 week post-weaning between the different sow parities.

Performance at 10 weeks post-weaning. Body weight and total litter weight at 10 weeks of age were not affected by the interaction between birth weight class × foster parity ($P > 0.05$), whereas gain to feed ratio between weaning and 10 weeks of age only tended to be affected ($P = 0.065$) by this interaction.

Body weight, total litter weight, ADG and post-weaning feed intake between weaning and 10 weeks of age were significantly affected by birth weight class ($P \leq 0.002$) and foster parity ($P \leq 0.036$). Piglets born light were 4.5 kg lighter at 10 weeks of age (28.0 kg, SD = 1.8 vs. 32.5 kg, SD = 1.9) and ate less between weaning and 10 weeks of compared with heavy piglets age

(657 g/d/piglet, SD = 66 vs. 758 g/d/piglet, SD = 68). Similar results were seen for ADG between weaning and 10 weeks of age. Post-weaning piglets reared by primiparous sows (29.7 kg, SD = 1.67) were significantly lighter at 10 weeks of age (P = 0.035) when compared with piglets reared by mid parity sows (31.2 kg, SD = 1.75); piglets reared by second parity sows (29.9 kg, SD = 1.65) only tended (P = 0.079) to weigh less than piglets reared by mid parity sows. No significant differences were observed between primiparous (568 g/day, SD = 36.4) and mid parity sow reared piglets (592 g/day, SD = 38.1) with respect to ADG between weaning and 10 weeks of age, whereas second parity sow reared piglets gained (561 g/day, SD = 35.8) significantly (P = 0.046) less when compared with mid parity sow reared piglets. At 10 weeks of age primiparous sow reared piglet tended (P = 0.054) to have a lower total litter weight (352 kg, SD = 20.5) compared with mid parity sow reared piglets (369 kg, SD = 21.5). Also post-weaning feed intake of primiparous sow reared piglets was significantly (P = 0.049) less between weaning and 10 weeks of age (690 g/d/piglet, SD = 61.5) compared with mid parity sow reared piglets (741 g/d/piglet, SD = 64.4); a tendency was observed between second (P = 0.065; 691 g/d/piglet, SD = 60.6) and mid parity sow reared piglets between weaning and 10 weeks of age. Gain to feed ratio did not differ between the different birth weight classes, but tended (P = 0.065) to be affected by foster parity with primiparous sow reared piglets tended (P = 0.072) to have a greater gain to feed ratio compared with mid parity sow reared piglets (0.825, SD = 0.035 vs. 0.801, SD = 0.036).

3.5 Discussion

Aiming for litter uniformity is an established practice in the industry (PIC, 2015; AHDB Pork, 2017a) and has been proven successful in improving the performance of light piglets (Douglas et al., 2014c; Huting et al., 2017). In the present study we investigated what is the best foster sow for light- and heavyweight piglets when reared in uniform litters as the issue currently presents a conundrum. Industry recommendations are often conflicting with respect to foster parity for piglets born lightweight (PIC, 2015; AHDB Pork, 2017a).

We hypothesized that teat morphometry of young sows maybe ideal for fostering lightweight piglets. Irrespectively of birth weight, piglets in general have a preference, immediately postpartum, for teats that are smaller in size (i.e. shorter and smaller in diameter) and positioned relatively close to the abdominal midline (Balzani et al., 2016a). Teats that meet the preferred morphometry are the anterior and posterior teat pairs (Balzani et al., 2016a) or teats from primiparous sows (Balzani et al., 2016b; Ocepek et al., 2016). As a result, piglets reared by young sows (parity 1 or 2) need less time between birth and the first suckle compared with piglets reared by older sows (parity 3 to 6) (Vasdal and Andersen, 2012). This is important because the longer it takes for a piglet to reach a teat, the less colostrum it consumes (Declerck et al., 2017) and the more prone it is to die (Devillers et al., 2011; Pandolfi et al, 2017). Given the impaired rooting response (Baxter et al., 2008) and reduced locomotion (Vanden Hole et al., 2018) of piglets born light, teat accessibility and morphology may be of particular importance for them and may not only influence their efficiency to reach and massage the teats during early life (Tuchscherer et al., 2000; Baxter et al., 2008), but also throughout lactation. On the other hand, the lower milk yield seen in primiparous sows (Beyer et al., 2007; Ngo et al., 2012; Quesnel et al., 2015), hinders individual piglet pre-weaning growth performance. Primiparous sow reared piglets were weaned >10% lighter than multiparous sow reared piglets (Bierhals et al., 2011; Miller et al., 2012; Carney-Hinkle et al., 2013) and this difference was sustained post-weaning (Miller et al., 2012). Nonetheless, the aforementioned studies evaluating the effect of foster parity on piglet performance have confounded their data with birth weight (Craig et al., 2017), or focused on the average piglet (1.44 kg) (Bierhals et al., 2011). For instance, due to limited cross-fostering piglets reared by primiparous sows weighed around 10-15% less at birth compared with those reared by multiparous sows (Miller et al., 2012; Carney-Hinkle et al., 2013). Furthermore, the effect foster parity may have on pre- and post-weaning performance may be more detrimental for heavy than light piglets. Cross-fostering heavy piglets to primiparous sows may adversely affect their performance due the lower milk yield (Beyer et al., 2007; Ngo et al., 2012; Quesnel et al., 2015) and the lower weight gain may result in more even sized piglets at weaning compared with heavy piglets reared by older sows. To that end, in the present study cross-fostering was applied and focused on light piglets but also heavy piglets to exacerbate the effect of foster sow parity. Furthermore, a differentiation was made between second and mid parity sows (parity 3 to 5). Second parity sows may be a good alternative for light piglets with respect to teat size and milk yield, compared with mid- and primiparous sows, respectively.

Although, not shown here, the relative back fat and body weight loss of the sows were not influenced by birth weight, foster parity or their interaction. The hypothesized interaction between birth weight class × foster parity as presented here only influenced body weight at d 10, with heavy piglets being disadvantaged when reared by primiparous and mid parity sows compared with second parity sows. No differences between foster parities were seen for light piglets. Nevertheless, foster parity did influence the pre- and post-weaning performance of piglets irrespectively of birth weight, thus may have influenced light and heavy piglets in a similar way. Primiparous sow reared piglets were weaned lighter and remained light post-weaning. This is in agreement to the results of Ferrari et al. (2014), who retrospectively created birth weight classes and found that primiparous sow reared piglets, irrespectively of birth weight, had a greater probability for low performance up to 6 weeks of age than piglets reared by multiparous sows. However, although second and mid parity piglets were weaned with a similar body weight, post-weaning second parity piglets performed less reaching a similar weight at 10 weeks of age compared with primiparous sow reared piglets whereas mid parity sow reared piglets performed best.

The significant greater pre-weaning removal rate as a result of weight loss for heavy piglets reared by mid parity sows compared with heavy piglets reared by primiparous and second parity sows, may be the result of differences in udder and teat quality. Firstly, udder quality deteriorates with increasing parity (Appel et al., 2016). Multiparous sows (parity ≥ 4) are more at risk for mastitis metritis agalactia, mostly seen in the posterior teat pairs (Baer and Bilkei, 2005), resulting in greater sow removal rates due to udder problems compared with primiparous sows (Engblom et al., 2007) and may result in less functional teats/piglet. Secondly, growth variation between the different teat pair locations due to differences in teats milking ability (Kim et al., 2000; Ogawa et al., 2014) becomes more apparent with increasing parity (primiparous versus multiparous sows: parity ≥ 2) (Dyck et al., 1987; Nielsen et al., 2001). These differences may result in more competition and missed suckling bouts and thus variable growth rates within litter and may explain why heavy piglets reared by mid parity sows were removed in greater quantities and performed considerably less during early life (d 10) compared with similar sizes piglets reared by primiparous and second parity sows respectively. Our experiment cannot distinguish whether the improved pre-weaning performance (> d 10) of the piglets reared by mid parity sows is due to reduced litter size, which resulted from piglet removal, increased creep feed consumption or any other factor associated with sow parity.

To our knowledge, this is the first study that has evaluated the effect of foster parity on creep feed consumption of piglets of various birth weights. Milk yield usually plateaus in the third week of lactation (~d 18) (Hansen et al., 2012), limiting piglet performance. It has been shown previously, that heavy piglets reared in uniform litters tried to compensate for their insufficient milk intake by consuming creep feed (Huting et al., 2017). This may suggest that fostering heavy piglets on primiparous sows may stimulate solid feed intake. Although, the numerical differences for creep feed intake and consumer class distribution for heavy piglets as shown here support this hypothesis, the high variation between and within litters may have resulted in the lack of significance for the interaction between birth weight class × foster parity. Yet, foster parity influenced the likelihood for a piglet to become consumer or non-consumer. Significantly less primiparous and mid parity sows reared piglets were considered non-consumers (< 30%) compared with second parity sows reared piglets (70%). Although, second parity sows are thought to have a similar milk yield compared with mid parity sows (Beyer et al., 2007; Ngo et al., 2012; Quesnel et al., 2015; Strathe et al., 2017), the results here suggest otherwise. The fact that piglets reared by primiparous and mid parity sows ate greater amounts of creep feed, implies that they had to compensate for the insufficient milk intake, whereas piglets reared by second parity sows hardly consumed creep feed. The discrepancy amongst our findings and those of the aforementioned studies warrant further research and the assessment of milk yield with multiparous sows (parity ≥ 2) fostering similar sized piglets.

As expected creep feed intake was low for light piglets compared with heavy piglets (Huting et al., 2017). Nevertheless, light piglets that did start eating creep feed did so considerably late (> d 21) compared with heavy piglets. This may suggest that light piglets have lower milk requirements to support their reduced growth capacity (Foxcroft et al., 2006) or that differences in gut maturity (Michiels et al., 2013) affect light piglet ability to consume creep feed. However, others suggest that birth weight does not affect the digestive capacity of piglets small intestine, but that stomach size might be piglets limiting factor (Huygelen et al., 2015)

The positive effect creep feed intake has on subsequent performance has been well documented (Bruininx et al., 2002; Sulabo et al., 2010; Huting et al., 2017). Also here, despite the lower growth rate during the initial 3 weeks of lactation, piglets considered high consumers were able to outperform non-consumers during the last week before weaning. The beneficial effects of creep feed provision on performance however is more pronounced during the post-weaning period (Bruininx et al., 2002; Sulabo et al., 2010; Huting et al., 2017). Piglets from all consumer classes, irrespectively of being considered low, moderate or high consumer, were ≥ 1 kg heavier at 10 weeks of age compared with non-consumers. The familiarization with solid feed during lactation is suggested to increase feed intake during the immediate post-weaning period positively influencing growth (Bruininx et al., 2002). Because the number of consumers per foster parity were unbalanced, we were unable to formally test the effect of the interaction between consumer class × foster parity on post-weaning performance. Therefore, we can only speculate the basis of the cumulative probability of consumer classes differences seen pre-weaning for the different foster parities and its effect on post-weaning performance. Although piglets reared by primiparous sows were weaned 6% lighter than piglets reared by second parity sows, this difference disappeared by week 10 of age. This is most likely a result of difference in pre-weaning creep feed intake. The combination of the high creep feed intake and similar weaning weights compared with second parity sow reared piglets on the other hand, most likely enabled mid parity sows reared piglets to outperformed the rest at 10 weeks of age represented by a greater post-weaning feed intake and a 1.25 kg heavier body weight.

3.6 Conclusion

As expected piglets born lightweight remained smaller pre- and post-weaning, compared with piglets born heavyweight. The absence of a significant interaction between birth weight class × foster parity suggests that foster sow parity influenced pre- and post-weaning performance of all piglets in a similar way. Nevertheless, the lower weaning weights for primiparous sows reared piglets compared with piglets reared by second and mid parity sows suggests a reduced milking ability of primiparous sows, and despite the high number of consumers of primiparous reared piglets they remained among the lightest post-weaning. Although, the highest number of consumers were seen for primiparous and mid parity sow litters, a direct link between consumer class and foster parity on post-weaning performance could not be made. The body weight difference as seen at weaning between primiparous and second parity sows reared piglets disappeared post-weaning which may be a result of the low pre-weaning solid feed intake of piglets reared by second parity sows. The relatively high weaning weight of piglets reared by mid parity sows and their high pre-weaning creep feed intake, resulted in a significant greater post-weaning gain and weight at 10 weeks of age. Overall, the results unequivocally suggest that irrespective of piglet size, piglets should ideally be fostered to mid parity sows. The results also justify long term performance monitoring to reach conclusions on how pre-weaning manipulations affect performance outcomes to slaughter.

Chapter 4.

Once small always small? To what extent morphometric characteristics and post-weaning starter regime affect pig lifetime growth performance

4.1 Abstract

The aim of this study was to determine the effect of piglet morphometric characteristics and starter regime on postnatal growth. Some piglets born light are able to grow faster than others and identifying which piglets are more at risk to remain light and at which growth stages of growth is essential. A nutrient enriched starter regime may allow lightweight pigs to improve their post-weaning growth. A total 1487 newly born piglets from 137 litters originating from 8 consecutive farrowing batches were followed from birth to weaning (d 28) and finishing (d 99). At birth morphometric measurements were taken, including body mass index (BMI), ponderal index (PI) and birth weight: cranial circumferences (BiW:CC). At weaning pigs were randomly allocated to the one of two experimental regimes: either a nutrient enriched regime with a 20% higher essential amino acids: energy ratio or a standard regime. Piglets were retrospectively allocated to 4 different weight classes using percentiles at birth, weaning and finishing, with class 1 representing the lightest and class 4 the heaviest class. A series of novel statistical models were used to determine which factors were able to predict performance. For birth weight class 1 piglets, BMI (P = 0.003) and birth weight relative to birth litter (P = 0.026) were positively associated with pre-weaning performance, whereas BiW:CC (P = 0.011) and weaning weight (P = 0.001) were positively associated with post-weaning growth. Post-weaning the best predictors of piglets weaned light (weaning weight class 1) were PI (P = 0.037), BiW:CC ($P < 0.001$), and weaning weight ($P < 0.001$). Starter regime did not influence ($P > 0.05$) post-weaning performance. Our results show that not all light pigs are the same and that their performance is under the influence of body shape rather than birth weight. Therefore, pig producers should discriminate between light pigs based on birth characteristics to improve the effectiveness of intervention strategies at the different stages of growth. Irrespective of weight class piglets did not benefit from the essential amino acids enriched regime applied.

4.2 Introduction

Slow growing pigs are more at risk to be delayed in all-in-all-out systems, resulting in remixing, increasing the potential for disease transmission, but most importantly contributing to considerable production losses (e.g. costs of feed, labour and penalties at slaughter) (Calderón Díaz et al., 2017a). However, it has been suggested that some pigs born light may have the potential to compensate during suckling (Quiniou et al., 2002) and subsequent growth stages (Paredes et al., 2012; Douglas et al., 2013; He et al., 2016). It is therefore important to identify which pigs are most likely to remain light throughout the production cycle and may require attention. Birth- (Quiniou et al., 2002; Calderón Díaz et al., 2017a) and weaning-weight (de Grau et al., 2005; Paredes et al., 2012; Douglas et al., 2013; He et al., 2016) have been identified as predictors for post-weaning growth. Morphometric characteristics at birth, on the other hand, predict survivability (e.g. body mass index, ponderal index, head shape; Baxter et al., 2008; Hales et al., 2013) and may be utilised to identify piglets that remain stunted throughout life (Douglas et al., 2016) or potentially benefit from intervention strategies such as specialised feeding. Different outcomes can be expected between piglets that have been born light for gestational age, e.g. light but short and stocky (Foxcroft et al., 2006; Douglas et al., 2016), and piglets that have suffered from growth restriction in utero which might be forever compromised (Wu et al., 2006). However, the evidence about the effect of body shape at birth on subsequent performance is scarce and lacks a life time performance approach.

One strategy that has been shown to be effective in improving the performance of pigs weaned light are high specification starter regimes (Beaulieu et al., 2010b; Douglas et al., 2014a); pigs weaned light have a poor start, but under the influence of an improved nutritional regime may be able to improve their performance. However, the regimes studied previously (Beaulieu et al., 2010b; Douglas et al., 2014a) have altered the ingredient composition considerably, making it impossible to identify which specific nutrients resource(s) would be most beneficial. Slow growing pigs are suggested to have a lower feed intake and lower serum concentrations of essential amino acids (He et al., 2016) compared to their fast growing siblings. The low feed intake of lightweight pigs (Nissen and Oksbjerg, 2011; Vieira et al., 2015) and possibly higher protein turnover in relation to their size (Thureen et al., 2003), suggest that lightweight pigs may exhibit improved performance when fed nutrient enriched diets that are high in essential amino acids (Tokach, 2004). The objectives of this study were: 1) to assess the influence of morphometric characteristics at birth on performance to finisher stage and whether these can differentiate between pigs that are able to exhibit an improved performance pre- and post-weaning; and 2) whether a nutrient enriched starter regime could contribute to an improved post-weaning performance of piglets weaned light.

4.3 Materials and methods

The experiment was conducted at Cockle Park Farm (Newcastle University, Morpeth, Northumberland, United Kingdom). The study was sponsored by AHDB (Agriculture and

Horticulture Development Board) Pork and Primary Diets. All animals were maintained in accordance to the recommendations for the welfare of livestock following UK legislations (Defra and Red Tractor UK farm assurance scheme) and the experiment was approved by the Animal Welfare and Ethical Review Body (AWERB project ID no. 419) of Newcastle University. All newly born piglets (n = 1487) of the 137 sows (i.e. 137 litters) that farrowed during 8 consecutive farrowing batches were followed to finisher stage (~14 weeks of age and 45 kg body weight).

4.3.1 *Pre-weaning management*

Following a 3-week cycle, sows of different parity were moved on Monday to the farrowing unit (farrowing crate dimensions 237 x 194 cm); those that had not farrowed by Thursday, were induced (23.9 % of the sows) with a Prostaglandin analogue (Planate; Intervet UK, Walton, United Kingdom). All sows were Large White x Landrace, inseminated with Hylean boar semen (Hermitage Seaborough, Ltd, Devon United Kingdom). They were fed a home-milled meal twice a day (08:00 and 15:00 h) and water was available *ad libitum* throughout lactation. The temperature in the farrowing unit was maintained at 21˚C (20.7˚C, range 18.2 to 26.9˚C).

AHDB Pork guidelines for cross-fostering (AHDB Pork, 2017a) were followed, to help piglets born light reduce competition and fit piglet mouths to the teat size of the sow. Cross-fostering was applied within the first 3 days post-partum to improve litter uniformity and to equalize litter size matching the number of piglets with the number of functional teats and milking ability of the sow (litter size range 10 to 15). During the first two days of life piglets were locked into the creep area (once a day; 0800 h), whilst the sow was eating, to minimize crushing. An infrared heat lamp (InterHeat; LPB300S 230v 50-60Hz, 250W) was located in the covered creep area and wood shavings (Goodwills Wood Shavings, Ponteland, Newcastle Upon Tyne, UK) were provided as bedding. Piglets had unlimited access to a water nipple drinker. Within the first 12 h after birth piglets had their teeth clipped. At ~3 days of age, piglets were tail docked and received an intramuscular iron injection. All piglets had access to creep feed from 10 days of age which was fed in small quantities (a handful) on the floor of the covered creep area. The creep was an equal mixture (50:50) of diet 1 of the standard and nutrient enriched starter regimes (see section 'Post-weaning starter regime').

4.3.2 *Post-weaning management*

Piglets were weaned at approximately 28 days of age (d 27.7, SD = 1.1) and were vaccinated for *M. hyopneumoniae* (1 ml; M+PAC; Intervet UK, Walton, United Kingdom) and porcine circovirus type 2 (1 ml; Inglevac Mycoflex; Boehringer Ingelheim, Ingelheim, Germany). They were pseudo randomly mixed to form groups of approximately 20 similar sized pigs/pen (range 9 to 24 pigs/pen), whilst balancing for sex, and moved to a fully slatted nursery accommodation. The number of pigs per pen was dependent on the number of pigs available per batch, ensuring a similar stocking density between pens and batches consistent with UK legislations. The nursery accommodation consisted of 6 separate environmental rooms, with approximately 3 rooms per batch. Pen size, where appropriate, was adjusted creating a minimum of 4 pens (each pen 183 x 340 cm of 20 to 25 pigs per pen depending on pig size) to a maximum of 8 pens (each pen 183 x 170 cm of a maximum of 12 pigs/pen) per room. All pigs had *ad libitum* access to water via nipple drinkers. The initial room temperature in the nursery accommodation was set at 26˚C (24.6˚C, range 20.7 to 27.2˚C) and reduced by approximately 0.2˚C each day to a minimum of 22˚C (23.4˚C, range 21.5 to 26.7˚C).

When moved to the on-site grower accommodation (d 61, SD = 1), pigs were fed the same home-milled meal and remained in the same post-weaning group. Groups of < 12 pigs were mixed to create groups of ~20 pigs/ pen (pen dimensions 320 x 210 cm). At approximately 13-14 weeks of age (d 96.9, SD = 6.6) pigs were moved again to a fully slatted finisher building (pen dimensions 500 x 304 cm) and were fed a commercial 'finisher' pelleted diet.

4.3.3 *Experimental procedures*

Pre-weaning procedures. Piglets were weighed to the nearest 1 g within 12 h post-partum (birth weight, kg), and individually identified by ear tagging (Dentag, Toptags, Kelso, UK). Morphometric measurements were taken from each individual piglet, including crown to rump length (CRL, cm), snout to crown length (head length HL, cm), abdominal circumferences (AC, cm) and cranial circumferences (CC, cm). Abdominal circumferences, was taken at the anterior side of the umbilicus cord. Crown rump length (m) was used to calculate the ponderal index (PI; birth weight, kg/CRL, m^3) and body mass index (BMI; birth weight, kg/CRL, m^2) (Douglas et al., 2016). Additional variables were created as an indicator of head size in relation to body weight: 1) birth weight: cranial circumferences (BiW:CC, kg/cm) (Douglas et al., 2016) and 2) snout to crown length: birth weight (HL:BiW, cm/kg) (Poore and Fowden, 2004).

At the point of tail docking litter composition (foster litter), including sow and piglet identification number, was recorded. The general health of piglets was examined on a daily basis in which pig(let)s posture (i.e. hunched back), breathing (including coughing and sneezing), activity (e.g. mobility, lameness, responsiveness), and faecal consistency was assessed; deaths, including cause of death where possible, were recorded. Piglet ear tags were

Table 4.1 Ingredient composition on an as-fed basis and chemical analysis of the post weaner feeds used. Pigs were randomly allocated to either a nutrient enriched or a standard starter regime. Diet 1 was fed until 2 kg was consumed, and diet 2 until 3 kg were consumed per pig. Diet 3 was fed *ad libitum*.[1]

Diet	1		2		3
Regime	Standard	Nutrient enriched	Standard	Nutrient enriched	
Ingredient g/kg					
Micronized barley	75.0	75.0	75.0	75.0	100.0
Wheat	105.0	93.8	365.1	353.7	529.7
Micronized wheat	150.0	150.0	50.0	50.0	-
Micronized oats	100.0	100.0	50.0	50.0	-
Fishmeal	75.0	75.0	50.0	50.0	25.0
Soya bean meal	160.0	160.0	220.0	220.0	260.0
Pig weaner vitamin/ trace element supplement[2]	5.0	5.0	5.0	5.0	5.0
Dried skim milk powder	75.0	75.0	30.0	30.0	-
Whey	225.7	225.7	118.1	118.1	34.7
L-Lysine HCL	1.80	5.70	3.10	6.80	3.70
DL-Methionine	1.70	2.90	2.00	3.20	2.10
L-Threonine	0.50	2.40	0.90	2.70	1.10
L-Tryptophan	0.20	0.80	0.20	0.80	0.10
L-Valine	0.00	2.30	0.40	2.50	0.40
Vitamin E	0.04	0.40	0.20	0.20	0.20
Benzoic acid	5.00	5.00	5.00	5.00	5.00
Limestone flour	-	-	1.30	1.30	-
Dicalcium phosphate	1.80	1.80	7.30	7.30	15.1
Salt	-	-	1.40	1.60	3.60
Binder (LignoBond DD)[3]	-	-	-	-	4.20
Sodium bicarbonate	0.10	1.90	5.00	6.80	-
Soya oil	17.3	17.2	10.0	10.0	10.1
Analysed composition, % as fed					
CP	21.1	22.1	21.9	22.8	21.5
Crude fibre	1.85	1.95	2.20	2.10	2.45
Moisture	10.4	9.70	10.0	10.1	11.0
Ash	4.75	5.15	6.10	6.40	5.60
Calculated composition, % as fed or as specified					
DE, MJ/kg	15.3	15.3	14.7	14.8	14.4
NE, MJ/kg	10.5	10.5	10.2	10.2	10.1
Calcium	0.77	0.77	0.77	0.77	0.75
Phosphorus	0.66	0.66	0.64	0.64	0.67
Lactose	20.0	20.0	10.0	10.0	2.50
Lysine[4]	1.40	1.70	1.35	1.64	1.25
Methionine	0.56	0.68	0.54	0.66	0.50
Methionine + Cysteine	0.84	0.96	0.83	0.94	0.79
Threonine	0.84	1.02	0.81	0.98	0.75
Tryptophan	0.27	0.32	0.26	0.31	0.24
Arginine	1.15	1.15	1.20	1.20	1.20
Histidine	0.50	0.50	0.49	0.48	0.47
Isoleucine	0.87	0.87	0.82	0.82	0.76
Leucine	1.56	1.55	1.44	1.43	1.32
Valine	0.98	1.19	0.95	1.15	0.88
Phenylalanine + Tyrosine	1.57	1.56	1.54	1.53	1.48

[1] Diets were supplied by Primary Diets, ABAgri, Ripon, North Yorkshire, United Kingdom

[2] It provided per kilogram of complete diet 11,500 IU of vitamin A, 2,000 IU of vitamin D_3, 100 IU of vitamin E, 4 mg of Vitamin K, 27.5 µg of vitamin B_{12}, 15 mg of pantothenic acid, 25 mg of nicotinic acid, 150 µg of biotin, 1.0 mg of folic acid, 160 mg of Cu ($CuSO_4$), 1.0 mg of iodine ($Ca(IO_3)_2$), 150 mg of Fe ($FeSO_4$), 40 mg of Mn (MnO), 0.25 mg of Se (bone morphogenetic protein), and 110 mg Zn ($ZnSO_4$).

[3] Borregaard LignoTech, Sarpsborg, Norway.

[4] All amino acids are expressed on a standardized ileal digestible (SID) basis

replaced by larger ear tags (Suretag flag, Dalton tags, Newark Nottinghamshire, UK) and piglets were individually weighed at weaning (d 27.7, SD = 1.1).

Post-weaning starter regime. At weaning, piglets were randomly allocated to either a nutrient enriched or a standard 3-stage starter regime (Primary Diets, ABAgri, Ripon, North Yorkshire, UK). Diet 1 and 2 of the nutrient enriched regime (Table 4.1) were supplemented with additional synthetic essential amino acids L-lysine, DL-methionine, L-threonine, L-tryptophan and L-valine, in order to achieve 20 % higher essential amino acids: energy ratio when compared to the standard diet, while maintaining the same NE and ensuring the appropriate ratios to lysine were maintained; the standard regime met NRC recommendations (NRC, 2012). By 7 weeks of age (d 48.0, SD = 0.9) all pigs had finished the first 2 starter diets. Diet 3 of both the nutrient enriched and standard regimes were identical.

For either regime, diet 1 was fed until 2 kg of feed were consumed and diet 2 until 3 kg of feed were consumed per pig. Diet 3 was fed *ad libitum* up to 9 weeks of age when pigs were moved to the grower accommodation. A power analysis was done using the PROC POWER statement in SAS version 9.4 (SAS inst. Inc. Cary, NC) to determine the required number of pens based on the results of previous study (Douglas et al., 2014a). A total of 70 nursery pens of animals were part of the experiment; 36 pens (n = 679) were fed the standard and 34 pens (n = 683) were fed the nutrient enriched starter regime.

Post-weaning procedures. Until movement to the grower facility (d 61.5, SD = 1.2), pigs were weighed once a week. At the same time the amount of feed offered and refused was recorded to estimate weekly feed intake. Pigs that lost weight during the first week post-weaning were weighed individually and daily during two successive days; those that kept losing body weight were removed from the experiment (see 'Statistical Analysis' section as to how this was addressed in the final models). Two hundred and six pigs (15.5 %) were sold as growers (d 74.8, SD = 1.9). The remainder of the pigs (n = 1121) were individually weighed at finisher stage (d 98.8, SD = 0.9).

4.3.4 *Statistical Analysis*

All statistical models were performed with SAS using mixed models (PROC MIXED) unless stated otherwise. The residual variance of the data was tested for normality using the UNIVARIATE procedure. Several covariance structures were tested, but variance components resulted in the lowest Akaike Information Criterion (AIC) with an AIC difference of > 4 considered substantial (Anderson, 2008). Data were expressed as least square means (LSM), with approximate standard errors of the differences of means (SED) unless stated otherwise. Statistical significance was assessed at the 5% level and tendencies were set at 10%.

Performance per pen. The effect of starter regime on post-weaning performance and coefficient of variation (CV) within a pen was assessed using PROC MIXED. The experimental unit was pen average blocked by room nested within farrowing batch; a weight statement was used to account for differences in the number of pigs per pen. Sex was added to the preliminary model as covariate.

Absolute performance per body weight class. Pigs were retrospectively assigned to body weight classes based on 25% percentiles (Douglas et al., 2013) creating 4 groups at birth, weaning, and finisher. Class 1 represented the lightest (bottom 25 %) and 4 the heaviest (top 25 %) pigs. Body weight classes created included all pigs that were alive or remained on site at the start of a specific stage of production (e.g. birth, weaning and finisher). Classes were created both within batch and over the entire period, however classes that were created within batch resulted in the best model fit. The experimental unit for all mixed models was piglet, blocked by farrowing batch. To account for any litter or pen effects piglets were blocked by: (1) sow (birth or foster sow) nested within farrowing batch for evaluating pre-weaning performance, and (2) pen x room nested within farrowing batch for evaluating post-weaning performance. In the post-weaning mixed model main effects of interest were body weight class, starter regime and their interaction. As classes were created retrospectively and piglets were allocated to the different starter regimes on the basis of their weaning weight and not birth weight, weaning weight was inserted in the model for birth weight class to account for weaning weight differences at the start of the treatment. In the preliminary models farrowing batch, sex, total number of pigs born, birth litter/ parity, foster litter/ parity, pre-weaning litter size, age and post-weaning group size were inserted as covariates where appropriate. As a result of mortality and pig removals due to weight loss or sickness, pre-weaning litter and post-weaning group size were corrected using the following formula over a given period:

> Litter/Group size = [(total time (h) piglets reside in the foster litter/ pen)/ 24 h]/ total period in d

An additional variable 'pen variation' was created (pen variation = average body weight class within pen) based on birth weight or weaning weight class and was added to all post-weaning analysis. Table 4.2 specifies the final model descriptions after removal of nonsignificant covariates used for the different objectives.

Table 4.2 Summary of final models used after removal of nonsignificant covariates. Within batch, birth, weaning, finisher weight classes were created retrospectively using percentiles resulting in 4 (25%) classes. At weaning pens were randomly allocated to one of the starter regimes: standard vs. nutrient enriched starter regime.

Objective	Parameter analysed	Unit	Model type	Fixed effects	Covariates	Random Effects	Weight
1) Effect of body weight class[1] and starter regime on absolute performance	Birth weight	Piglet	PROC MIXED	Birth weight class, Sex	Total born, Batch	Foster sow nested within Batch, VC[3]	-
	Pre-weaning performance			Body weight class[1], Sex, Starter regime, body weight class × Starter regime	Litter size[2], Foster parity, Age, Batch		-
	Post-weaning performance				Age, Batch, Weaning weight[4], Pen variation[5]	Room × pen nested within Batch, VC[3]	-
	Post weaning performance	Pen mean	PROC MIXED	Starter regime	Batch, Pen variation[5], Sex	Room nested within Batch, VC[3]	Group size[2]
2) Effect of body weight class[1] and starter regime on class change	Final body weight class (e.g. weaning weight or finisher weight class) 1, 2, 3, or 4[6]	Piglet	PROC LOGISTIC, descending	Body weight class[1,7], Starter regime[7], body weight class × Starter regime	Sex, Age	-	-
3) Effect of pigs characteristics on class change	Final body weight class (e.g. weaning weight or finisher weight class) 1, 2, 3, or 4[6]	Piglet[8]	PROC LOGISTIC, descending	Pre-weaning ADG or various morphometric characteristics	Sex, Age	-	-

[1] Body weight classes were birth weight and weaning weight class
[2] Pre-weaning litter size/ group size post-weaning = [(total time (h) piglets reside within litter/ pen)/24 h]/ total period in d
[3] Random effect type variance components (VC)
[4] Weaning weight was only inserted in the model assessing the effect on birth weight class on post-weaning performance.
[5] Pen variation based on weaning weight class representing the average body weight class per pen. The latter, was only inserted in the model assessing the effect of weaning weight class on post-weaning performance and the model with pen mean as experimental unit.
[6] The response variable (final body weight class) was formatted to enable to estimation of class change for the intermediate classes
[7] The reference for body weight class (e.g. birth weight or weaning weight class) was set to the final body weight to be tested. The reference for starter regime was the standard regime.
[8] The model was performed for each body weight class separate (i.e. class 1, 2, 3, or 4), omitting body weight class as independent variable

A chi-square test was carried out to test whether the reason for removal and pre- and post-weaning mortality was different among pigs of different body weight classes and whether this was affected by starter regime and/or sex. In addition, a chi-square was used to test whether the number of pigs that decreased, remained or increased at least one body weight class at weaner or finisher (Douglas et al., 2013; Paredes et al., 2014) was different among the different body weight classes.

Cluster analysis. A principal component analysis (PCA) was performed using PROC FACTOR to determine whether there is a distinct group within birth weight and weaning weight class 1 piglets able for compensatory growth during respectively the pre- and post-weaning period. An additional variable for birth weight in relation to birth litter average were calculated using the following formula (Paredes et al., 2012; Hales et al., 2013):

Relative birth weight = [Birth weight piglet/ mean birth weight birth litter]

For birth weight class 1 piglets 10 variables were considered, including birth weight, relative birth weight and the various morphometric characteristics (AC, CC, CRL, BMI, PI, HL, BiW: CC and HL: BiW). The above variables plus pre-weaning ADG and weaning weight were considered for weaning weight class 1 piglets. Principal components with an Eigenvalue greater than 1 were retained in the model and were used in the cluster analysis (PROC CLUSTER) using the Ward method to minimise within-cluster variance. The number of clusters were determined on the basis of fit statistics (e.g. Cubic Clustering Criteria, Pseudo F and t^2 statistics; (Milligan and Cooper, 1985)) and the dendrogram. The effect of the clusters on the different variables that were considered in the PCA and its effect on pre- and post-weaning performance were analysed using mixed models adjusting the degrees of freedom to unequal variance with denominator degrees-of-freedom (DDF) Satterhweite and studentized maximum modulus (SMM) enabling multiple comparison.

Probability for compensatory growth. Two different logistic regressions (PROC LOGISTIC) were conducted to identify whether piglets from different body weight classes differ in their ability to change class in later life, and whether this was under the influence of starter regime and the various morphometric characteristics. The first logistic regression tested whether piglets of birth weight class 1 to 4 had a different probability to end up in weaning weight class 1 to 4. A similar model was conducted between birth weight – finisher weight and weaning weight - finisher weight. The effects of interest was body weight class (birth weight or weaning weight class), starter regime and their interaction. In the second logistic regression, pre-weaning ADG and various morphometric characteristics were added to determine whether pig ability to change body weight class decreased or increased (log odds ± SE) with one unit increase in the predictor variable. For both regressions, the response variable of interest (e.g. weaning weight and finisher weight class) had more than two levels and was therefore formatted to enable the estimation of piglet probability to end up in one of the intermediate body weight classes (class 2 or 3), with zero representing everything other than the body weight class of interest. The reference value was set to the final body weight class of interest using the DESCENDING option to ensure the likelihood to end up in the 'highest' body weight class was tested.

Multivariate analysis. All potential predictor variables were fitted in a univariate mixed model to test their effect on pre- and post-weaning performance. Only predictor variables that were significant ($P < 0.05$) in the univariate model were taken forward in the multivariate analysis. Multivariate models were built following a forward and backward stepwise procedure only leaving factors in that had a probability below 0.05 and using the AIC criteria to determine which model fitted best. Different models were built for variables that were highly correlated ($r > 0.70$) to ensure the variance inflation factor (PROC REG) remained low (< 2).

4.4 Results

An overview of pre-and post-weaning farm characteristics can be found in Table 4.3. Sex significantly affected birth ($P = 0.006$) and weaning weight ($P = 0.043$), with males being weaned heavier (respectively 1.47 kg, SD = 0.33 and 7.26 kg, 2.20) than females (respectively 1.46 kg, SD = 0.35 and 7.09 kg, SD = 2.08). Certain morphometric characteristics, including AC, CC, PI, and BMI, were also significantly (at most $P < 0.05$) lower for females than male piglets. However, the ratio of head size to body weight (i.e. BiW:CC) tended ($P = 0.094$) to be higher in females than in male piglets. Weak positive correlations were found between birth weight and weaning weight ($r = 0.497$, $P < 0.001$) and birth weight and pre-weaning ADG ($r = 0.326$, $P < 0.001$), whereas a high correlation was found between weaning weight and pre-weaning ADG ($r = 0.970$, $P < 0.001$).

Performance per pen. Sex was equally distributed across treatments ($P > 0.05$); weaning weight and pen CV (d 28) did not differ between starting regimes. Post-weaning performance (d 28 to 61) was not affected by starter regime; body weight and pen CV at various stages of production along with feed intake and gain to feed ratio were not significantly different ($P > 0.05$) between pigs allocated to the nutrient enriched or standard regime.

Absolute performance per birth weight class. Table 4.4 shows the total number of piglets per birth weight class at the different stages of production. The highest pre-weaning mortality rate

(21.1%) was observed for piglets born light (class 1), compared to piglets of birth weight class 2 - 4 (*P* < 0.001). Most (46.8 %) of these birth weight class 1 piglets were non-viable at birth or died of starvation, of which 67.6% were male and 32.4% female pigs (*P* = 0.003). The number of piglets per starter regime was unbalanced (*P* < 0.001) for birth weight class 2 and 4 piglets. Significantly (*P* < 0.001) more piglets of birth weight class 2 were allocated to the standard versus nutrient enriched regime. The opposite was the case for piglets of birth weight class 4 (*P* < 0.001). Within pen variation was not significantly different across treatments (*P* < 0.05). Total post-weaning removal (including weight loss, sickness, and mortality) was significantly affected by birth weight class. Significantly (*P* = 0.028) more piglets of birth weight class 1 (3.7%; 72.7% males and 27.3% females, *P* = 0.033) were removed than piglets born heavy (class 4, 1.1%). Also, piglets of birth weight class 2 tended (*P* = 0.065) to be removed in higher quantities compared to piglets of birth weight class 4 (3.1% vs. 1.1%). Total post-weaning removal was affected by starter regime (*P* = 0.040), with the highest removal observed for piglets fed the nutrient enriched regime (*n* = 19, 2.9%) compared to those fed the standard regime (*n* = 8, 1.2%).

Table 4.3 Pre- and post-weaning production characteristics. All newly born piglets from 137 litters originating from 8 consecutive farrowing batches were followed from birth to weaning (d 28) and finishing (d 99) following normal farm practises.

Characteristics		Range
At birth		
Number of piglets born alive, total	1487	-
Males, %	57	-
Litter size	12.6	2 to 19
Still born	92 (5.4%)	-
Mummified	40 (2.3%)	-
Crushed within 12h post-partum	23 (1.3%)	-
Birth weight, kg	1.47 (SD = 0.34)	0.454 to 2.45
Litter CV[1]		-
Birth	18.6 (SD = 5.6)	
After cross-fostering	12.2 (SD = 4.9)	
Pre-weaning		
Number of piglets cross-fostered, %	57.7	-
Pre-weaning mortality, %[1]	8.4	-
Weaning weight, kg[2]	7.18 (SD = 1.60)	2.18 to 12.4
Body weight post-weaning[2]		
d 48, kg	14.7 (SD = 2.8)	4.93 to 25.4
d 61, kg	22.7 (SD = 4.0)	9.40 to 36.6
d 74, kg[3]	32.6 (SD = 2.9)	23.8 to 38.8
d 99, kg	44.9 (SD = 6.4)	21.6 to 67.4

[1] Based on the piglets that were alive at the first processing (< 12 h post-partum).
[2] Pigs were weighed at weaning (d 27.7; SD = 1.1), 3 weeks (48.0; SD = 0.9), 5 weeks (d 61.5; SD = 1.2), and 10 weeks post-weaning (d 98.8, SD = 0.9).
[3] Pigs that were sold earlier (d 74.8, SD = 1.9)

Table 4.4 Total number of pigs pre- and post-weaning per birth weight class. Within batch birth weight classes were created retrospectively using percentiles (25%) resulting in 4 different groups. Class 1 represents the lightest piglets and class 4 the heaviest. At weaning pens were randomly allocated to one of the starter regimes: standard vs. nutrient enriched regime.

Birth weight class	1		2		3		4		Total		
Starter regime	Standard	Nutrient enriched	Standard	Nutrient enriched	Standard	Nutrient enriched	Standard	Nutrient enriched	Standard	Nutrient enriched	*P*-value[1]
Number of pigs[2]											
d 0	374		371		372		370		1487		1.000
d 28	148	147	202[a]	150[b]	192	169	137[b]	217[a]	679	683	<0.001
d 48	146	139	199[a]	143[b]	190	167	137[b]	215[a]	672	664	<0.001
d 61	146	138	198[a]	143[b]	190	167	137[b]	215[a]	671	663	<0.001
d 97[3]	142	133	189[a]	128[b]	176[a]	146[b]	115[b]	191[a]	564	557	<0.001
d 75[4]	15[a]	5[b]	19	6	12	10	12	20	58	41	0.164
d 99[5]	127	128	170[a]	122[b]	164[a]	136[b]	103[b]	171[a]	515	498	<0.001

[a,b] Absolute values within birth weight class with different superscripts differ significantly ($P < 0.05$) between starter regimes.
[1] A chi square test was used to test the overall difference between the different birth weight classes x starter regime (entire row, excluding total).
[2] Pigs were followed from birth (d 0), weaning (d 27.7, SD = 1.1), grower (d 61.5, SD = 1.2), to finisher (d 96.9, SD = 6.6).
[3] The number of animals at d 97 consists of: 1) pigs that were sold as growers (i.e. 206 pigs were sold as growers (32.6 kg, SD = 2.9) at an age of d 75 (d 74.8, SD = 1.9) of which 99 were weighed and the rest (n = 107) no additional weights were taken); and 2) the pigs (n = 1013) that reached finisher age on site (d 98.8, SD = 0.9).
[4] The number of animals at d 75 only consist of the 99 pigs that were weighed and sold as growers (32.6 kg, SD = 2.9) at an age of d 75 (d 74.8, SD = 1.9).
[5] Only those pigs that reached finisher age on site (d 98.8, SD = 0.9).

Table 4.5a shows the effect of birth weight class and starter regime on subsequent performance. Birth weight class significantly ($P < 0.001$) affected piglet body weight throughout the productive period; pigs in class 1 remained lighter throughout the different stages of production, weighing > 3 kg lighter (40.9 kg, SD = 10.7) at day 97 than piglets born heavier (44.0 kg, SD= 10.5, 44.8 kg, SD = 10.4, and 45.6 kg, SD = 10.7 for respectively class 2, 3, and 4). Although starter regime did not affect body weight at d 48 ($P > 0.05$), it tended to influence piglet body weight at d 61 ($P = 0.059$). Piglets that were allocated to the standard regime weighed 1.00 kg heavier at the end of the nursery (23.1 kg, SD = 8.9) than piglets fed the nutrient enriched regime (22.1 kg, SD = 8.7). However, at finisher (d 97) the effect of starter regime was absent ($P > 0.05$). Apart from weaning weight ($P < 0.001$), there was no significant interaction between birth weight class × starter regime at later stages of production ($P > 0.05$); the significant interaction at weaning was a result of diet and pig allocation: following normal farm practices piglets were grouped together on the basis of weaning weight and not birth weight.

Absolute performance per weaning weight class. A total of 1362 piglets were weaned of which $n = 355$ were considered lightweight (weaning weight class 1), $n = 342$ pigs belonged to weaning weight class 2, $n = 329$ to weaning weight class 3, and $n = 336$ to weaning weight class 4 ($P > 0.05$). The number of pigs per starter regime within weaning weight class was unbalanced ($P < 0.001$). Significantly ($P = 0.001$) more pigs of weaning weight class 1 were allocated to the nutrient enriched ($n = 155$) versus standard regime ($n = 200$). Similarly, more pigs of weaning weight class 2 ($P < 0.001$) and 3 ($P = 0.073$) were allocated to the standard (respectively $n = 199$ and $n = 176$) vs. the nutrient enriched regime (respectively $n = 143$ and $n = 153$). The opposite ($P = 0.003$) was the case for piglets of weaning weight class 4 ($n = 149$ for standard vs. $n = 187$ for nutrient enriched). The differences in number of pigs per starter regime was a result of adhering to normal farm practices: animals were not allocated to different pens on the basis of their actual body weight but on the basis of size (e.g. small, medium, or large). In addition, since classes were created post-hoc, each pen often consisted of a mixture of various weaning weight classes rather than one class only. Nevertheless, pen variation was not significantly different across treatments ($P > 0.05$). Total post-weaning removal was 2.0%, with pigs in weaning weight class 1 being removed in the highest quantity (6.8%, $P < 0.001$), compared to pigs of weaning weight class 2, 3, and 4 (< 1.0%).

Table 4.5b shows the effect of weaning weight class and starter regime on subsequent performance. Weaning weight class influenced pigs body weight throughout the different stages of growth. Pigs of the lightest weaning weight class (weaning weight class 1), remained light throughout the different stages of production weighing almost 8.0 kg lighter at finisher

Table 4.5 Effect of birth weight class (a), weaning weight (b) class and starter regime on subsequent performance. Per batch birth weight (d 0) and weaning weight (d 28) class were determined retrospectively by grouping piglets into 4 different classes (25%) using percentiles at birth and weaning. Class 1 represents the lightest piglets and class 4 the heaviest. At weaning pens were randomly allocated to one of the starter regimes (standard vs. nutrient enriched). Data are expressed as LSM ± SED.

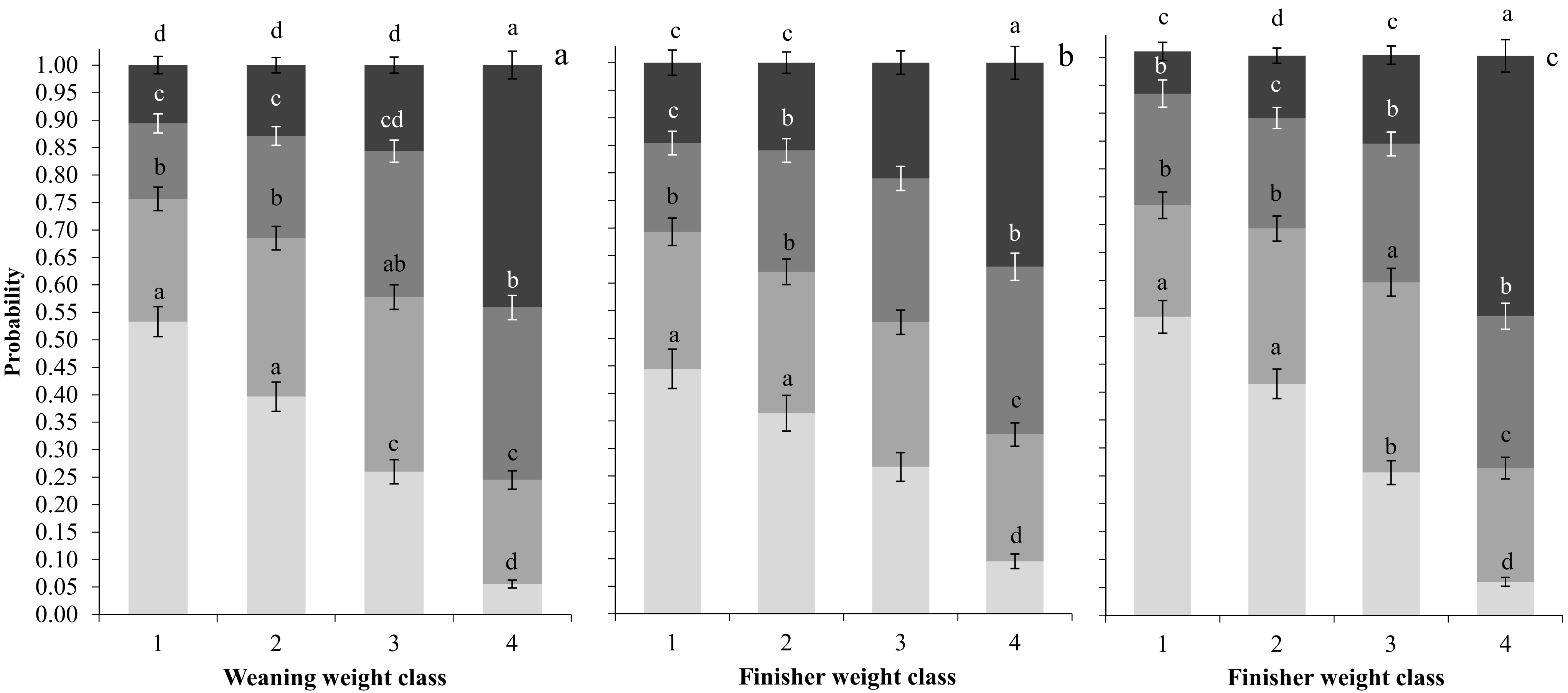
a

Birth weight class	1		2		3		4			Significance		
Starter regime	Standard	Nutrient enriched	Standard	Nutrient enriched	Standard	Nutrient enriched	Standard	Nutrient enriched	SED	Birth weight class	Starter regime	Birth weight class × Starter regime
Body weight[1], kg												
d 0	1.02		1.37		1.58		1.87		0.001	<0.001	-	-
d 28	6.67[a]	6.01[b]	7.05	6.96	7.40	7.59	7.64[b]	8.09[a]	0.041	<0.001	0.729	<0.001
d 48	14.1	13.6	14.6	14.5	14.9	15.0	15.4	15.3	0.039	<0.001	0.312	0.139
d 61	22.1	21.0	22.8	22.4	23.1	22.8	23.8	23.3	0.077	<0.001	0.059	0.386
d 97	42.5	40.6	44.6	43.7	44.6	44.7	44.8	45.1	0.197	<0.001	0.514	0.369
Average daily gain, g/d												
d 0 - 28	186		202		213		218		0.413	<0.001	-	-
d 28 - 48	343	313	365	360	377	382	405	399	1.95	<0.001	0.312	0.111
d 48 - 61	586	547	611	584	611	582	622	593	3.00	<0.001	0.036	0.993
d 28 - 61	441	406	463	449	471	462	492	476	2.06	<0.001	0.075	0.298
d 61 - 97	580	552	615	590	606	609	606	620	3.04	<0.001	0.520	0.302

b

Weaning weight class	1		2		3		4			Significance		
Starter regime	Standard	Nutrient enriched	Standard	Nutrient enriched	Standard	Nutrient enriched	Standard	Nutrient enriched	SED	Weaning weight class	Starter regime	Weaning weight class × Starter regime
Body weight[1], kg												
d 28	5.42	5.30	6.65	6.66	7.60	7.68	9.11	9.17	0.012	<0.001	0.920	0.194
d 48	12.6	12.4	14.3	14.3	15.2	15.0	16.7	16.9	0.046	<0.001	0.825	0.747
d 61	20.1	19.2	22.4	22.0	23.5	23.2	25.7	25.4	0.075	<0.001	0.212	0.765
d 97	40.1	39.6	43.9	43.3	45.8	44.0	47.3	47.4	0.204	<0.001	0.436	0.462
Average daily gain, g/d												
d 28 - 48	339	331	379	380	378	372	387	392	2.09	<0.001	0.825	0.776
d 48 - 61	538	514	597	579	604	617	649	640	3.00	<0.001	0.198	0.303
d 28 - 61	423	399	467	454	473	465	497	491	2.18	<0.001	0.219	0.737
d 61 - 97	576	549	608	601	625	590	614	629	3.60	<0.001	0.332	0.194

[a,b] Within body weight class numbers with different superscripts differ significantly ($P < 0.05$).
[1] Pigs were weighed within 12 h post-partum (d 0), at weaning (d 27.7, SD = 1.1), 3 weeks post weaning (d 48.0, SD = 0.9), grower (d 61.5, SD = 1.2), and finisher (d 96.9, SD = 6.6).



Significance	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.208	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Figure 4.1 Piglet cumulative probability to change body weight class between birth and weaning (a), birth and finisher (b), and weaning and finisher (c). Within batch, body weight classes were created using percentiles (25%) resulting in 4 groups. Class 1 represents the lightest pig, class 4 the heaviest. Data is represented in probability ± SE. Different colours represent body weight class, with respectively class 1 ■, class 2 ■, class 3 ■, and class 4 ■. The comparison is made between pigs of different body weight classes (i.e. birth weight or weaning weight class) estimating their probability to end up in one of the final body weight classes (i.e. weaning or finisher). Pigs were weighed within 12 h after birth (d 0), weaning (d 27.7, SD = 1.1), and finisher (d 98.8, SD = 0.9).
[a,b,c,d] Within body weight class (i.e. weaning, finisher) numbers with different superscripts differ significantly ($P < 0.05$)

compared to pigs weaned heavy (respectively 39.7 kg, SD = 12.3; and 47.5 kg, SD = 11.4). No difference ($P > 0.05$) in final weights (d 97) were observed between pigs from weaning weight class 2 and 3. Neither starter regime nor the interaction between starter regime × weaning weight class affected post-weaning performance ($P > 0.05$).

Growth between birth and subsequent stages. Figure 4.1a and 4.1b show the cumulative probability of the various birth weight classes to change class between birth and weaning, and birth and finisher respectively. The likelihood to end up light at weaning and finisher increased with decreasing birth weight class. Birth weight class 1 piglets fed the nutrient enriched regime had a higher likelihood ($P < 0.001$) to remain light (0.603, SD = 0.043 vs. 0.398, SD = 0.044) and a lower likelihood to end up heavy at finisher (0.055, SD = 0.010 vs. 0.103, SD = 0.016) than the same class piglets fed the standard regime.

Significant correlations were found between the different predictor variables assessed for each birth weight class separate as shown in Table 4.6. As expected BMI and PI were highly correlated for all birth weight classes. Figure 4.2 and 4.3 shows the effect of various morphometric characteristics on pig ability to change body weight class from respectively birth to weaning and from birth to finisher. Apart from HL the majority of morphometric characteristics affected class change of especially birth weight class 1 pigs. The effect of pre-weaning performance on pig ability to change body weight class between birth and finisher is summarised in Figure 4.4a. It is evident that for all birth weight classes, piglet odds to end up light at finisher decreased with one unit increase in ADG ($P < 0.001$).

Table 4.7 shows the final multivariate regression models for the various birth weight classes and the effect of different predictor variables on pre- and post-weaning ADG. The final multivariate regression model for birth weight class 1 pigs showed that relative birth weight ($P = 0.026$) and BMI ($P = 0.003$) were the most important factors for predicting the pre-weaning performance of birth weight class 1 pigs, being positively associated with growth. It has to be noted however, that relative birth weight ($P < 0.001$) was highly correlated (Table 4.6) with other variables that were significant in the univariate model (Table 4.8) such as birth weight ($r = 0.830$), BiW:CC ($r = 0.824$) and HL:BiW ($r = -0.780$). Although, significantly more ($P = 0.003$) birth weight class 1 pigs remained light (class 1) at weaning (56.1%), compared to those that were able to increase class (43.9%), birth weight class 1 pigs that were able to increase class pre-weaning, had a significant ($P < 0.001$) higher OR (95% CI); 5.11 [2.87, 9.10], 7.20 [3.59, 14.5], and 11.5 [2.53, 52.2] for respectively class 2-4, to end up heavy at finisher (finisher weight class 3 and 4) than pigs that remained light at weaning (reference). However, the OR to

Table 4.6 Rank correlations between predictor variables for piglets of a different birth weight class. Within batch, birth weight classes were created retrospectively using percentiles resulting in 4 (25%) classes: class 1 represents the lightest pig, class 4 the heaviest. Numbers in bold were variables that were considered highly correlated (r > +/- 0.70).[1,2]

Birth weight class 1

Predictor variable	BiW	Rel BiW	WW	ADG	CRL	HL	AC	CC	BMI	PI	BiW: CC	HL: BiW
Birth weight (BiW), kg	-											
Relative Birth weight (Rel BiW)[3]	**0.830**	-										
Weaning weight (WW), kg	0.431	0.367	-									
Pre-weaning ADG (ADG), g/day	0.327	0.291	**0.982**	-								
Crown to rump length (CRL), cm	**0.728**	0.650	0.230	0.171	-							
Snout to crown length (HL), cm	0.442	0.409	0.083	*ns*	0.396	-						
Abdominal circumference (AC), cm	**0.701**	0.552	0.194	0.131	0.557	0.313	-					
Cranial circumference (CC), cm	**0.782**	0.614	0.322	0.241	0.568	0.340	0.643	-				
Body mass index[4](BMI), kg/m^2	0.640	0.492	0.328	0.252	*ns*	0.213	0.411	0.509	-			
Ponderal index[5] (PI), kg/m^3	0.210	0.126	0.168	0.132	-0.500	*ns*	*ns*	0.173	**0.883**	-		
BiW: CC, kg/cm	**0.973**	**0.824**	0.415	0.316	**0.715**	0.436	0.651	0.620	0.620	0.200	-	
HL: BiW, cm/kg	**-0.935**	**-0.780**	-0.429	-0.335	-0.682	-0.195	-0.676	**-0.745**	-0.625	-0.222	**-0.916**	-

Birth weight class 2

Predictor variable	BiW	Rel BiW	WW	ADG	CRL	HL	AC	CC	BMI	PI	BiW: CC	HL: BiW
Birth weight (BiW), kg	-											
Relative Birth weight (Rel BiW)[3]	0.302	-										
Weaning weight (WW), kg	0.192	0.002	-									
Pre-weaning ADG (ADG), g/day	0.131	0.005	**0.981**	-								
Crown to rump length (CRL), cm	0.276	0.150	*ns*	*ns*	-							
Snout to crown length (HL), cm	0.224	0.124	*ns*	*ns*	0.171	-						
Abdominal circumference (AC), cm	0.246	0.123	*ns*	*ns*	0.228	*ns*	-					
Cranial circumference (CC), cm	0.384	*ns*	0.123	*ns*	*ns*	*ns*	0.169	-				
Body mass index[4](BMI), kg/m^2	0.263	*ns*	*ns*	*ns*	**-0.846**	*ns*	*ns*	0.117	-			
Ponderal index[5] (PI), kg/m^3	*ns*	*ns*	*ns*	*ns*	**-0.921**	*ns*	-0.140	*ns*	**0.983**	-		
BiW: CC, kg/cm	**0.820**	0.300	0.121	*ns*	0.236	0.180	0.155	-0.212	0.202	*ns*	-	
HL: BiW, cm/kg	-0.635	-0.148	*ns*	*ns*	*ns*	0.608	-0.155	-0.245	-0.252	-0.140	-0.521	-

Birth weight class 3

Predictor variable	BiW	Rel BiW	WW	ADG	CRL	HL	AC	CC	BMI	PI	BiW: CC	HL: BiW
Birth weight (BiW), kg	-											
Relative Birth weight (Rel BiW)[3]	0.120	-										
Weaning weight (WW), kg	0.123	*ns*	-									
Pre-weaning ADG (ADG), g/day	*ns*	*ns*	**0.975**	-								
Crown to rump length (CRL), cm	0.352	*ns*	*ns*	*ns*	-							
Snout to crown length (HL), cm	0.240	*ns*	*ns*	*ns*	0.186	-						
Abdominal circumference (AC), cm	0.191	0.137	0.130	*ns*	0.145	*ns*	-					
Cranial circumference (CC), cm	0.398	*ns*	*ns*	*ns*	*ns*	0.162	0.179	-				
Body mass index[4](BMI), kg/m^2	0.136	*ns*	*ns*	*ns*	**-0.872**	*ns*	*ns*	*ns*	-			
Ponderal index[5] (PI), kg/m^3	*ns*	*ns*	*ns*	*ns*	**-0.931**	-0.105	*ns*	*ns*	**0.986**	-		
BiW: CC, kg/cm	**0.786**	0.140	*ns*	*ns*	0.309	0.146	*ns*	-0.254	*ns*	*ns*	-	
HL: BiW, cm/kg	-0.626	*ns*	*ns*	*ns*	-0.141	0.605	-0.109	-0.194	-0.163	*ns*	-0.528	-

Birth weight class 4

Predictor variable	BiW	Rel BiW	WW	ADG	CRL	HL	AC	CC	BMI	PI	BiW: CC	HL: BiW
Birth weight (BiW), kg	-											
Relative Birth weight (Rel BiW)[3]	0.251	-										
Weaning weight (WW), kg	0.313	0.193	-									
Pre-weaning ADG (ADG), g/day	0.211	0.185	**0.984**	-								
Crown to rump length (CRL), cm	0.348	*ns*	0.227	0.179	-							
Snout to crown length (HL), cm	0.290	*ns*	0.160	0.148	0.208	-						
Abdominal circumference (AC), cm	0.337	0.237	0.206	0.165	0.151	*ns*	-					
Cranial circumference (CC), cm	0.536	*ns*	0.155	0.105	0.150	0.168	0.259	-				
Body mass index[4](BMI), kg/m^2	0.354	0.146	*ns*	*ns*	-0.746	*ns*	*ns*	0.216	-			
Ponderal index[5] (PI), kg/m^3	0.121	*ns*	*ns*	*ns*	**-0.875**	*ns*	*ns*	*ns*	**0.970**	-		
BiW: CC, kg/cm	**0.884**	0.266	0.280	0.187	0.332	0.251	0.249	*ns*	0.296	*ns*	-	
HL: BiW, cm/kg	**-0.784**	-0.248	-0.199	-0.107	-0.201	0.357	-0.302	-0.412	-0.354	-0.178	-0.699	-

[1] Pearson correlation test was used to estimate correlations between continuous variables that were normally distributed. Variables with a high correlation ($r \geq 0.70$) are in bold. Morphometric measurements were taken within 12 h post-partum, pigs were weighed at birth (d 0) and at weaning (d 27.7; SD = 1.1).

[2] *ns* = not significant ($P > 0.05$)

[3] Relative birth weight = (Birth weight piglet/ mean birth weight birth litter)

[4] Body mass index = birth weight (kg)/[crown rump length (m)]^2

[5] Ponderal index = birth weight (kg)/[crown rump length (m)]^3

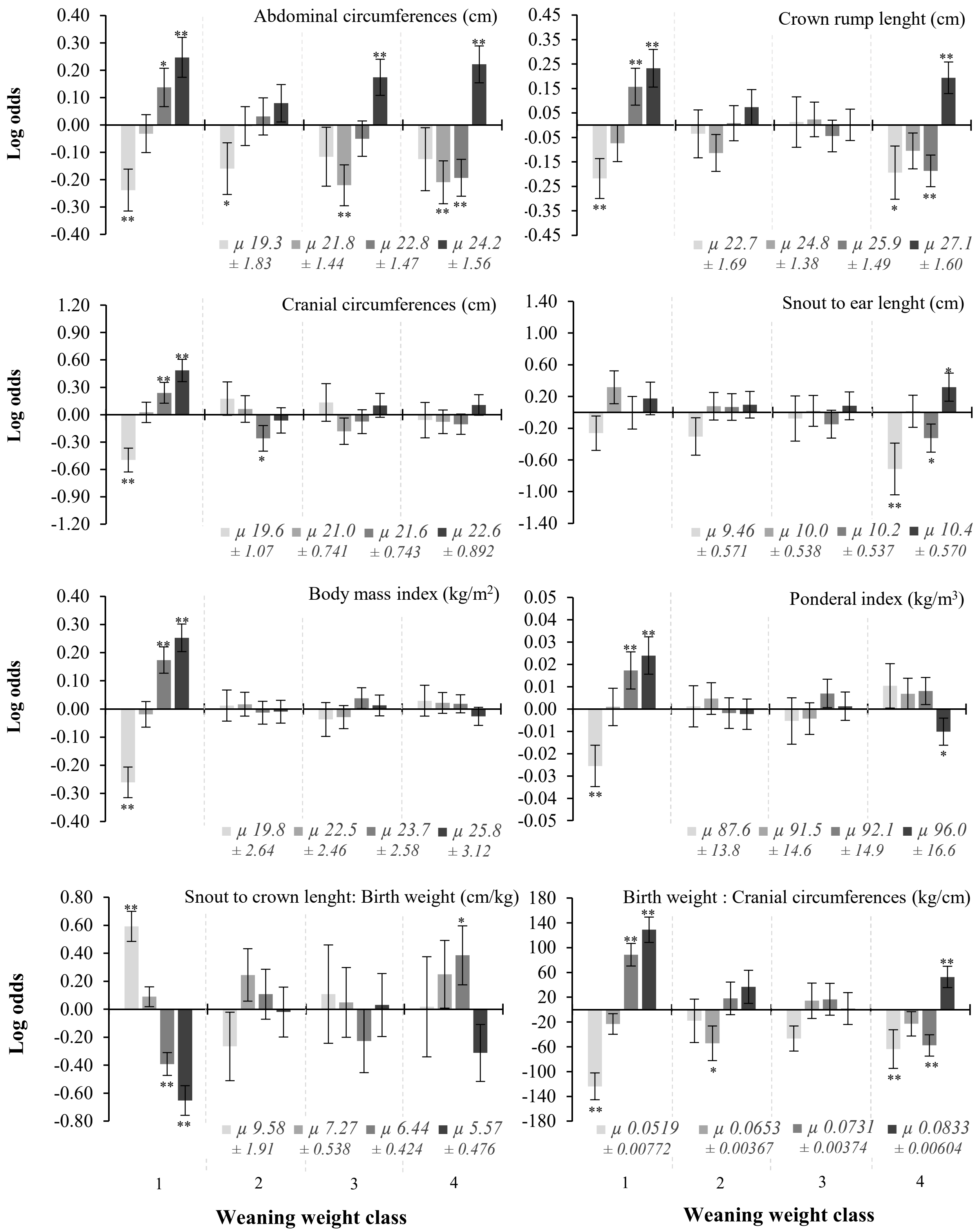


Figure 4.2 Effect of various morphometric characteristics on pig ability (log odds ± SE) to change body weight class between birth and weaning. Within batch, body weight classes were created using percentiles (25%) resulting in 4 groups. Class 1 represents the lightest pig, class 4 the heaviest. The different colours represent birth weight class, with respectively class 1 ■, class 2 ■, class 3 ■, and class 4 ■. Coefficients were estimated for each birth weight class separate. Morphometric measurements were taken within 12 h post-partum, pigs were weighed at birth (d 0) and again at weaning (d 27.7; SD = 1.1). The μ ± SED on the x-axis represent the average of the characteristic of interest for each birth weight class.** ($P < 0.05$), * ($P < 0.10$)

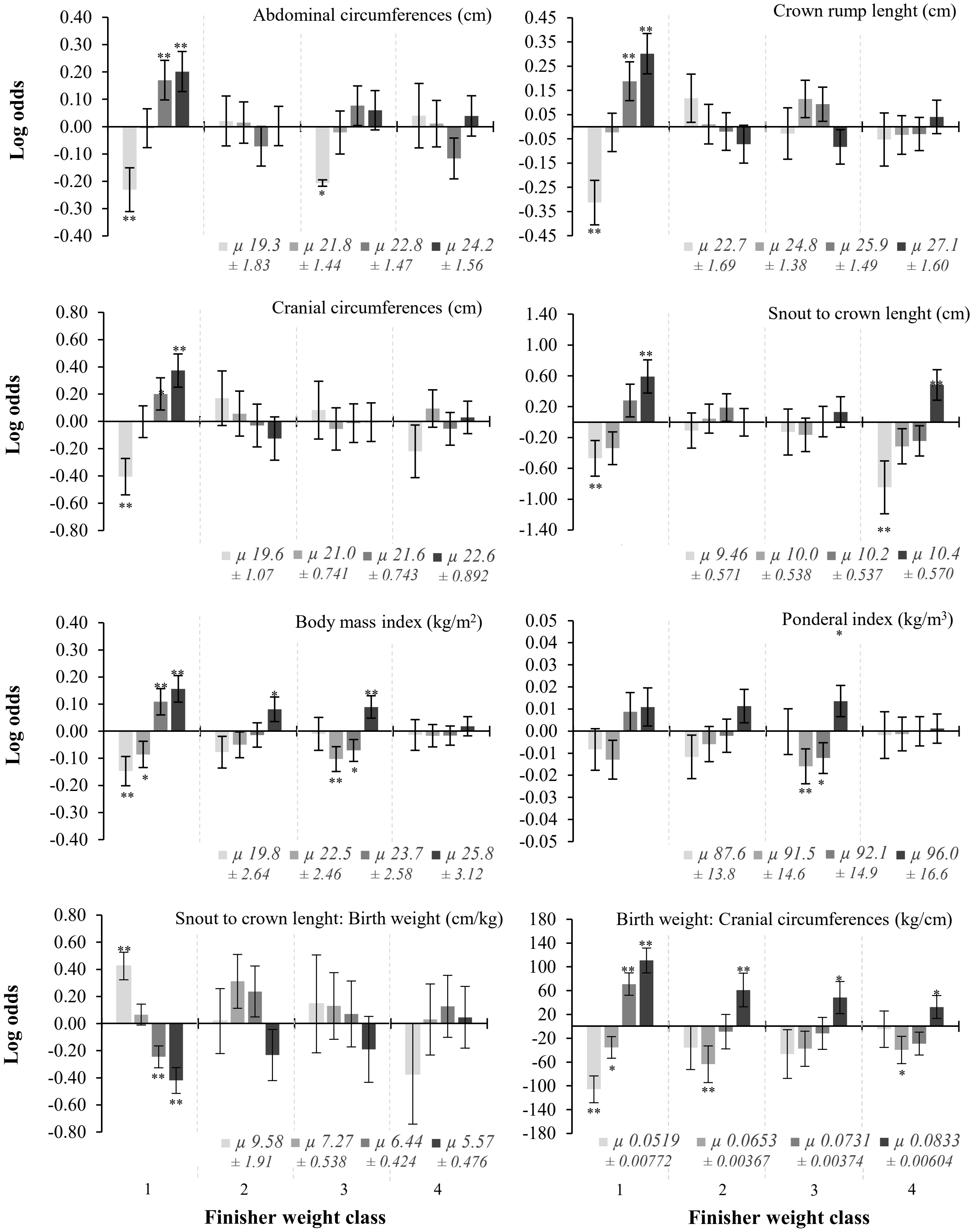


Figure 4.3 Effect of various morphometric characteristics on pig ability (log odds ± SE) to change body weight class between birth and finisher. Within batch, body weight classes were created using percentiles (25%) resulting in 4 groups. Class 1 represents the lightest pig, class 4 the heaviest. The different colours represent birth weight class, with respectively class 1 ■, class 2 ■, class 3 ■, and class 4 ■. Coefficients were estimated for each birth weight class separate. Morphometric measurements were taken within 12 h post-partum, pigs were weighed at birth (d 0) and again at finisher (d 98.8; SD = 0.9). The μ ± SED on the x-axis represent the average of the characteristic of interest for each birth weight class. ** ($P < 0.05$), * ($P < 0.10$)

Table 4.7 Final multivariate models (coefficient ± SE) of different predictor variables for pre- (d 0 to 28) and post-weaning ADG (d 28 to 99) for piglets from different body weight classes. Within batch, body weight classes were created using percentiles (25%) resulting in 4 groups at birth (d 0) and weaning (d 27.7, SD = 1.1). Class 1 represents the lightest, class 4 the heaviest pigs. Morphometric measurements were taken within 12 h post-partum and pigs were weighed at birth, weaning and again at finisher (d 98.8; SD = 0.9).

Body weight class	Birth weight class								Weaning weight class			
Average daily gain, g/day	d 0 – 28				d 28 - 99				d 28 - 99			
	Class 1	Class 2	Class 3	Class 4	Class 1	Class 2	Class 3	Class 4	Class 1	Class 2	Class 3	Class 4
Predictor variable												
Birth weight, kg	-	-	-	54.5 (21.0)	-	-	-	-	-	-	-	-
Relative birth weight[1]	47.5 (21.1)	-	-	71.7 (27.1)	-	-	-	-	-	-	75.2 (33.9)	-
Snout to crown length, cm	-	-	-	12.1 (5.05)	-	-	-	-	-	-	-	-
Abdominal circumference, cm	-	-	3.55 (1.77)	-	-	-	-	-	-	5.89 (2.27)	-	-
Body mass index[2], kg/m^2	3.20 (1.06)	-	-	-	-	-	-	-	-	-	-	-
Ponderal index[3], kg/m^3	-	-	-	-	-	-	-	-	0.688 (0.319)	-	-	-
Birth weight: Cranial circumference, kg/cm	-	1729 (674)	-	-	2107 (824)	-	-	-	1128 (409)	-	-	1542 (581)
Sex[4]	-	11.5 (4.53)	-	-	-	-	-	-	-	-20.7 (8.59)	-	-
Weaning weight, kg	-	-	-	-	15.4 (4.50)	12.0 (4.24)	11.0 (3.76)	15.1 (3.42)	36.2 (6.57)	-	-	-
Pre-weaning ADG, g/day	-	-	-	-	-	-	-	-	-	-0.670 (0.261)	-	-

[1] Relative birth weight = (Birth weight piglet/ mean birth weight birth litter)
[2] Body mass index = birth weight (kg)/[crown rump length (m)]2
[3] Ponderal index = birth weight (kg)/[crown rump length (m)]3
[4] The coefficient reflects that of male, female was set as reference (0)

end up heavy at finisher did not differ (*P* > 0.05) among birth weight class 1 pigs that increased class (e.g. weaning weight class 2, 3 or 4 piglets). The best fit multivariate model for post-weaning performance (Table 4.7) of birth weight class 1 piglets consisted of only BiW:CC (*P* = 0.011) and weaning weight (*P* = 0.001).

Table 4.8 Statistical significance (*P* - value) of the different predictor variables fitted in the univariate models for piglets of a different birth weight class for ADG (g/d) between d 0 to 28 and d 28 to 99. Within batch, birth weight classes were created retrospectively using percentiles resulting in 4 (25%) classes. Class 1 represents the lightest pig, class 4 the heaviest. Morphometric measurements were taken within 12 h post-partum, pigs were weighed at birth (d 0), at weaning (d 27.7; SD = 1.1), and at finisher (d 98.8; SD = 0.9).

	d 0 - 28				d 28 - 99			
Predictor variable	Class 1	Class 2	Class 3	Class 4	Class 1	Class 2	Class 3	Class 4
Birth weight, kg	**<0.001**	**0.017**	0.615	**<0.001**	**<0.001**	0.423	0.221	0.256
Relative birth weight[1]	**<0.001**	0.886	0.913	**<0.001**	**<0.001**	0.555	0.355	0.449
Weaning weight, kg	-	-	-	-	**<0.001**	**0.005**	**0.004**	**<0.001**
Pre-weaning ADG, g/day	-	-	-	-	**<0.001**	**0.014**	**0.011**	**<0.001**
Sex	0.941	**0.019**	0.702	0.449	0.346	0.870	0.846	0.698
Starter regime	-	-	-	-	0.186	0.296	0.568	0.891
Crown to rump length, cm	0.631	0.703	0.940	**0.002**	**0.012**	0.653	0.729	0.664
Snout to crown length, cm	0.702	**0.050**	0.699	**0.003**	0.104	0.944	0.791	0.051
Abdominal circumference, cm	0.201	**0.040**	**0.046**	**0.009**	0.050	0.601	0.795	0.426
Cranial circumference, cm	**0.007**	0.815	0.462	0.085	0.073	0.745	0.583	0.437
Body mass index[2], kg/m^2	**<0.001**	0.370	0.724	0.861	**0.040**	0.543	0.191	0.194
Ponderal index[3], kg/m^3	**0.005**	0.527	0.810	0.237	0.486	0.658	0.268	0.246
Birth weight: Cranial circumference, kg/cm	**<0.001**	**0.018**	0.990	**<0.001**	**<0.001**	0.362	0.379	0.366
Snout to crown length: Birth weight, cm/kg	**<0.001**	0.929	0.974	**<0.001**	**<0.001**	0.656	0.272	0.679
Litter size pre-weaning[4]	0.120	0.064	0.166	0.632	0.825	0.174	0.159	**0.012**
Group size post-weaning[4]	-	-	-	-	0.827	0.797	0.778	**0.023**

[1] Relative birth weight = (Birth weight piglet/ mean birth weight birth litter)
[2] Body mass index = birth weight (kg)/[crown rump length (m)]^2
[3] Ponderal index = birth weight (kg)/[crown rump length (m)]^3
[4] Pre-weaning litter size/ group size post-weaning = [(total time (h) piglets reside within litter/ pen)/24 h]/ total period in d

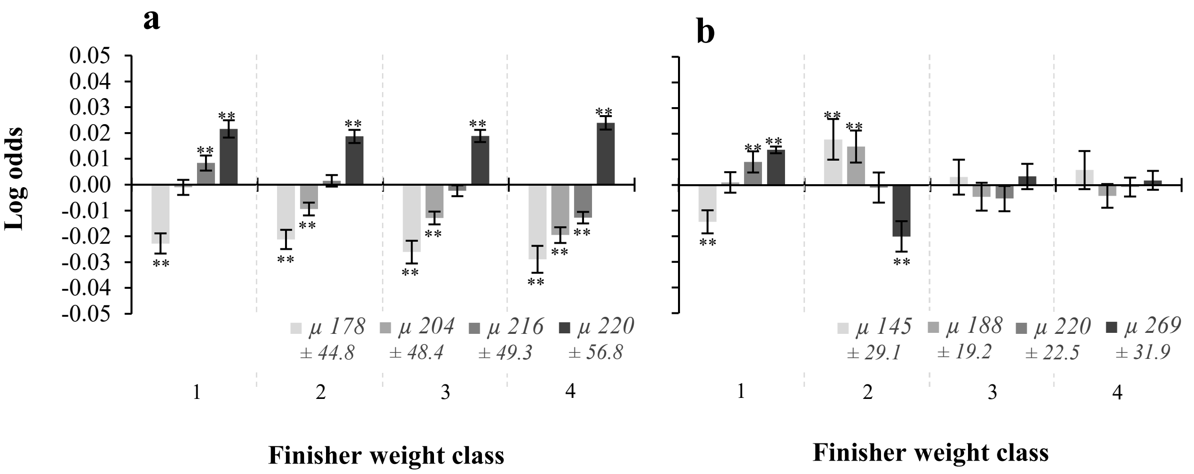


Figure 4.4 Effect of pre-weaning ADG (d 0 to 28) on pig ability (log odds ± SE) to change body weight class between birth and finisher (a) and weaning and finisher (b). Within batch, body weight classes were created using percentiles (25%) resulting in 4 groups. Class 1 represents the lightest pig, class 4 the heaviest. The different colours represent body weight class at birth or weaning, with respectively class 1 ■, class 2 ■, class 3 ■, and class 4 ■. Coefficients were estimated for each body weight class separate. Pigs were weighed at birth (d 0), at weaning (d 27.7; SD = 1.1), and at finisher (d 98.8; SD = 0.9). The μ ± SED on the x-axis represent the average of the characteristic of interest for each birth weight or weaning weight class. ** (*P* < 0.05), * (*P* < 0.10)

The principal cluster analysis of birth weight class 1 piglets showed that two principal components had an Eigenvalue greater than 1. Together they explained 79.6% of the total variation: 59.4% by principal component 1 and 20.2% by principal component 2. Three clusters were formed; the description of the different clusters based on the variables used in the PCA are shown in Table 4.9. The majority of the piglets belonged to cluster 1 (44.2%), followed by cluster 2 (34.6%) and cluster 3 (21.2%) piglets. Cluster 2 piglets were the lightest at birth, relatively lighter compared to their average birth litter and differed significantly with respect to the various morphometric characteristics from cluster 1 and 3 piglets. While piglets of cluster 1 and 3 were born with a similar birth weight, the differences in morphometric characteristics (i.e. HL, CRL, BMI, PI) suggest that piglets of cluster 1 were born proportionally long and thin compared to cluster 3 piglets. Pre-weaning mortality was significantly (P = 0.002) higher for cluster 2 piglets (34.1 %) compared to cluster 1 (16.4 %) and cluster 3 (21.5 %) piglets. Piglets belonging to cluster 2 were weaned significantly (P < 0.001) lighter (5.75 kg, SD = 1.46) compared to cluster 1 and 3 piglets (respectively 6.11 kg, SD = 1.54 and 6.33 kg, SD = 1.56), however post-weaning performance was not significantly (P > 0.05) different among the different clusters.

The majority of birth weight class 2 pigs were able to increase class between birth weight and weaning weight (44.9%) and birth weight and finisher weight (47.9%) compared to those that remained (respectively 31.3% and 25.3%) or decreased body weight class (respectively 23.9% and 26.7%). Those that decreased class pre-weaning, had a significant (P <0.001) lower OR (0.483 [0.273, 0.854]) to end up heavier at finisher (class 4) compared to birth weight class 2 pigs that remained or increased class, respectively class 2 (reference), 3 (1.38 [0.812, 2.36]) and 4 (3.28 [1.70, 6.31]). On the other hand, most pigs of birth weight class 3 decreased class between birth weight and weaning weight (40.2%) and birth weight and finisher weight (42.5%). Consequentially, birth weight class 2 and 3 piglets had a similar probability (P > 0.05) to end up in weaning weight class 3, finisher weight class 2, and finisher weight class 3 as shown in Figure 4.1a and 4.1b respectively. Sex (P = 0.012) and birth weight: CC (P = 0.012) were able to predict pre-weaning performance of birth weight class 2 pigs (Table 4.7) whereas, weaning weight was the sole variable in the multivariate model and was positively associated with post-weaning performance for birth weight class 2 to 4 pigs.

Growth between weaning and finisher. Weaning weight class 1 piglets had the highest likelihood (P < 0.05) to remain light (class 1 and 2) at finisher and were less likely to end up heavy at finisher (class 4) compared to weaning weight class 2 to 4 piglets (Figure 4.1c). Although significantly more weaning weight class 1 piglets (54.1%) remained light at finisher

(P = 0.047), 45.1% were able to increase class. Figure 4.4b shows the effect of pre-weaning ADG on piglet ability to change body weight class between weaning and finisher. Pre-weaning ADG only significantly influenced class change for piglets weaned below average (class 1 and 2). Class change between weaning weight and finisher weight was also significantly affected by the different morphometric characterises (Figure 4.5) and mostly affected weaning weight class 1 piglets.

Table 4.9 Cluster characteristics of birth weight class 1 piglets (smallest 25% at birth) clustered in different groups based on birth weight and various morphometric characteristics. Data are expressed as LSM ± SED.[1]

Cluster (%)	1 44.2%	2 34.6%	3 21.2%	SED	Significance
Cluster characteristics					
Body weight, kg					
d 0	1.10[a]	0.835[b]	1.10[a]	0.002	<0.001
Relative birth weight[2]	0.807[a]	0.610[b]	0.794[a]	0.002	<0.001
Morphometric characteristics					
Abdominal circumferences, cm	20.0[b]	17.9[a]	19.8[b]	0.051	<0.001
Cranial circumferences, cm	20.0[b]	18.7[a]	20.0[b]	0.014	<0.001
Snout to crown length, cm	9.64[a]	9.18[c]	9.47[b]	0.010	<0.001
Crown rump length, cm	23.9[a]	21.5[b]	21.8[b]	0.021	<0.001
Body mass index[3], kg/m^2	19.5[b]	18.0[c]	23.0[a]	0.032	<0.001
Ponderal index[4], kg/m^3	81.4[b]	83.9[b]	106[a]	0.183	<0.001
Birth weight: Cranial circumferences, kg/cm	0.0549[a]	0.0458[b]	0.0546[a]	0.0001	<0.001
Snout to crown length: Birth weight, cm/ kg	8.84[b]	11.3[a]	8.74[b]	0.025	<0.001

[a,b,c] Values with different superscripts differ significantly (P < 0.05).
[1] Pigs were weighed within 12 h post-partum (d 0).
[2] Relative birth weight = (Birth weight piglet/ mean birth weight birth litter)
[3] Body mass index = birth weight (kg)/[crown rump length (m)]^2
[4] Ponderal index = birth weight (kg)/[crown rump length (m)

The majority (P < 0.001) of piglets weaned light (weaning weight class 1) were born light (48.1%), the rest was weaned light but born heavier: birth weight class 2 (23.3%), 3 (15.7%) and 4 (12.8%). Piglets born heavier (birth weight class 2 to 4) but weaned light had a significantly (P <0.001) higher OR (respectively, 3.17 [1.80, 5.58], 3.60, [1.87, 6.92], and 3.67, [1.80, 7.48]) to end up heavy at finisher (class 4) compared to piglets of birth weight class 1 (reference). The multivariate regression model (Table 4.7) including piglets that were alive at finisher (d 99), suggests that BiW:CC (P < 0.001), PI (P = 0.037), and weaning weight (P < 0.001) were the best predictors for post-weaning performance, being positively associated with growth of weaning weight class 1 piglets. It has to be noted that BiW:CC was positively correlated to birth weight (r = 0.983), relative birth weight (r = 0.856) and various morphometric characteristics (r > 0.70) such as AC, CC, BMI, and HL:BiW (Table 4.10) that appeared to be significant in the univariate analysis (Table 4.11).

The description of the cluster analysis for weaning weight class 1 piglets based on the variables used in the PCA is shown in Table 4.12. Three principal components had an Eigenvalue greater

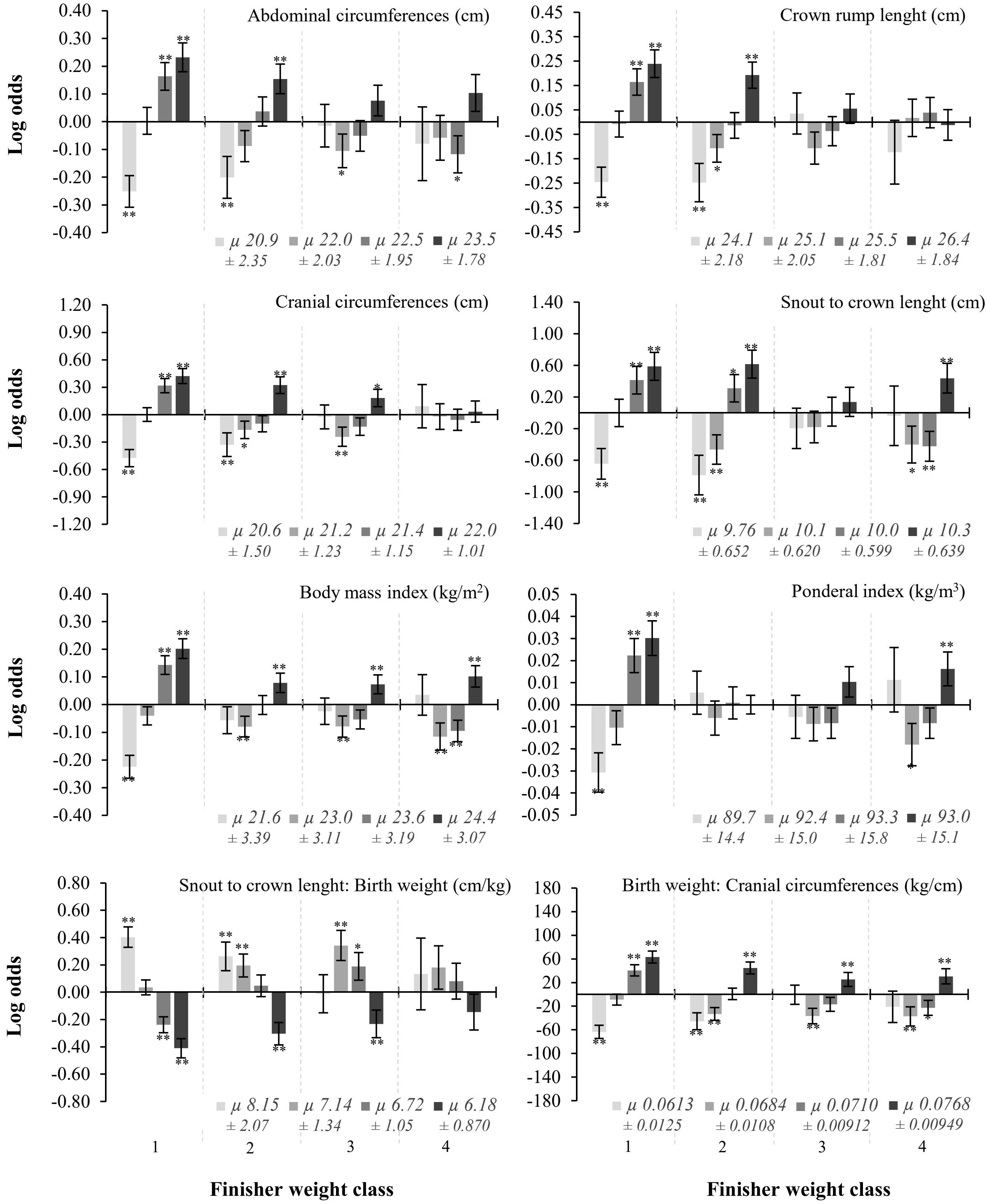


Figure 4.5 Effect of various morphometric characteristics on pig ability (log odds ± SE) to change body weight class between weaning and finisher. Within batch, body weight classes were created using percentiles (25%) resulting in 4 groups: class 1 represents the lightest pig, class 4 the heaviest. The different colours represent weaning weight class 1 ▪, class 2 ▪, class 3 ▪, and class 4 ▪**.** Coefficients were estimated for each weaning weight class separate. Morphometric measurements were taken within 12 h post-partum and pigs weaning weight and finisher weight were taken at respectively d 27.7 (SD = 11) and d 98.8 (SD = 0.9). The μ ± SED on the x-axis represent the average of the characteristic of interest for each weaning weight class. ** ($P < 0.05$), * ($P < 0.10$)

Table 4.10 Rank correlations between predictor variables for piglets of a different weaning weight class. Within batch, weaning weight classes were created retrospectively using percentiles resulting in 4 (25%) classes. Class 1 represents the lightest pig, class 4 the heaviest. Numbers in bold were variables that were considered highly correlated (r > +/- 0.70).[1,2]

Weaning weight class 1

Predictor variable	BiW	Rel BiW	WW	ADG	CRL	HL	AC	CC	BMI	PI	BiW: CC	HL: BiW
Birth weight (BiW), kg	-											
Relative Birth weight (Rel BiW)[3]	**0.854**	-										
Weaning weight (WW), kg	0.240	0.215	-									
Pre-weaning ADG (ADG), g/day	-0.151	*ns*	**0.906**	-								
Crown to rump length (CRL), cm	**0.825**	**0.750**	0.183	-0.124	-							
Snout to crown length (HL), cm	0.571	0.548	0.109	*ns*	0.493	-						
Abdominal circumference (AC), cm	**0.817**	**0.748**	0.140	-0.180	0.692	0.444	-					
Cranial circumference (CC), cm	**0.870**	**0.733**	0.225	-0.119	**0.725**	0.498	**0.780**	-				
Body mass index[4](BMI), kg/m^2	**0.757**	0.620	0.227	*ns*	0.271	0.425	0.624	0.669	-			
Ponderal index[5] (PI), kg/m^3	0.282	0.195	0.131	*ns*	-0.290	0.437	0.231	0.249	**0.836**	-		
BiW: CC, kg/cm	**0.983**	**0.856**	0.241	-0.140	**0.819**	0.571	**0.789**	**0.775**	**0.742**	0.273	-	
HL: BiW, cm/kg	**-0.932**	**-0.828**	-0.272	*ns*	**-0.797**	-0.399	**-0.807**	**-0.847**	**-0.723**	-0.273	**-0.925**	-

Weaning weight class 2

Predictor variable	BiW	Rel BiW	WW	ADG	CRL	HL	AC	CC	BMI	PI	BiW: CC	HL: BiW
Birth weight (BiW), kg	-											
Relative Birth weight (Rel BiW)[3]	**0.730**	-										
Weaning weight (WW), kg	0.127	*ns*	-									
Pre-weaning ADG (ADG), g/day	-0.390	-0.264	**0.758**	-								
Crown to rump length (CRL), cm	**0.746**	0.604	*ns*	-0.267	-							
Snout to crown length (HL), cm	0.526	0.413	0.113	-0.115	0.512	-						
Abdominal circumference (AC), cm	0.692	0.549	*ns*	-0.286	0.281	0.426	-					
Cranial circumference (CC), cm	**0.796**	0.534	0.189	-0.272	0.578	0.422	0.603	-				
Body mass index[4](BMI), kg/m^2	0.604	0.405	*ns*	-0.248	*ns*	0.185	0.354	0.503	-			
Ponderal index[5] (PI), kg/m^3	0.134	*ns*	*ns*	*ns*	-0.543	*ns*	*ns*	0.132	**0.869**	-		
BiW: CC, kg/cm	**0.974**	**0.742**	*ns*	-0.392	**0.739**	0.516	0.664	0.644	0.581	0.121	-	
HL: BiW, cm/kg	**-0.930**	**-0.724**	*ns*	0.387	-0.682	-0.281	-0.655	**-0.749**	-0.608	-0.173	**-0.918**	-

Weaning weight class 3

Predictor variable	BiW	Rel BiW	WW	ADG	CRL	HL	AC	CC	BMI	PI	BiW: CC	HL: BiW
Birth weight (BiW), kg	-											
Relative Birth weight (Rel BiW)3	0.670	-										
Weaning weight (WW), kg	0.123	*ns*	-									
Pre-weaning ADG (ADG), g/day	-0.301	-0.215	**0.805**	-								
Crown to rump length (CRL), cm	0.656	0.478	*ns*	-0.246	-							
Snout to crown length (HL), cm	0.497	0.386	*ns*	-0.183	0.420	-						
Abdominal circumference (AC), cm	0.675	0.513	*ns*	-0.217	0.487	0.306	-					
Cranial circumference (CC), cm	**0.828**	0.522	0.189	0.175	0.531	0.421	0.593	-				
Body mass index4(BMI), kg/m2	0.576	0.373	0.128	-0.111	-0.229	0.196	0.354	0.494	-			
Ponderal index5 (PI), kg/m3	0.192	*ns*	*ns*	*ns*	-0.613	*ns*	*ns*	0.176	**0.909**	-		
BiW: CC, kg/cm	**0.972**	0.674	*ns*	-0.321	0.638	0.472	0.636	0.669	0.559	0.176	-	
HL: BiW, cm/kg	**-0.919**	-0.644	-0.148	0.247	-0.593	-0.187	-0.655	**-0.780**	-0.561	-0.209	**-0.898**	-

Weaning weight class 4

Predictor variable	BiW	Rel BiW	WW	ADG	CRL	HL	AC	CC	BMI	PI	BiW: CC	HL: BiW
Birth weight (BiW), kg	-											
Relative Birth weight (Rel BiW)[3]	0.598	-										
Weaning weight (WW), kg	0.282	0.187	-									
Pre-weaning ADG (ADG), g/day	*ns*	*ns*	**0.908**	-								
Crown to rump length (CRL), cm	0.630	0.363	0.170	**0.968**	-							
Snout to crown length (HL), cm	0.432	0.203	0.242	0.145	0.315	-						
Abdominal circumference (AC), cm	0.627	0.489	0.191	*ns*	0.487	0.256	-					
Cranial circumference (CC), cm	**0.747**	0.447	0.294	*ns*	0.470	0.376	0.511	-				
Body mass index[4](BMI), kg/m^2	0.525	0.337	0.146	*ns*	-0.322	0.184	0.233	0.397	-			
Ponderal index[5] (PI), kg/m^3	0.133	*ns*	*ns*	*ns*	0.675	*ns*	*ns*	*ns*	**0.912**	-		
BiW: CC, kg/cm	**0.966**	0.582	0.237	*ns*	0.617	0.401	0.591	0.553	0.501	0.121	-	
HL: BiW, cm/kg	**-0.900**	-0.592	-0.178	*ns*	-0.568	*ns*	-0.591	-0.656	-0.483	-0.127	**-0.881**	-

[1] Pearson correlation test was used to estimate correlations between continuous variables that were normally distributed. Variables with a high correlation ($r \geq 0.70$) are in bold. Morphometric measurements were taken within 12 h post-partum, pigs were weighed at birth (d 0) and at weaning (d 27.7; SD = 1.1).
[2] *ns* = not significant ($P > 0.05$)
[3] Relative birth weight = (Birth weight piglet/ mean birth weight birth litter)
[4] Body mass index = birth weight (kg)/[crown rump length (m)]^2
[5] Ponderal index = birth weight (kg)/[crown rump length (m)]^3

Table 4.11 Statistical significance (*P* - value) of the different predictor variables fitted in the univariate models for piglets of a different weaning weight class for ADG (g/d) between d 28 and 99. Within batch, weaning weight classes were created retrospectively using percentiles resulting in 4 (25%) classes. Class 1 represents the lightest pig, class 4 the heaviest. Morphometric measurements were taken within 12 h post-partum, pigs were weighed at birth (d 0), at weaning (d 27.7; SD = 1.1), and at finisher (d 98.8; SD = 0.9).

	d 28 - 99			
Predictor variable	Class 1	Class 2	Class 3	Class 4
Birth weight, kg	**<0.001**	**<0.001**	0.074	**0.018**
Relative birth weight[1]	**<0.001**	**0.002**	**0.028**	0.056
Weaning weight, kg	**<0.001**	0.610	0.567	0.742
Pre-weaning ADG, g/day	**<0.001**	**<0.001**	0.445	0.553
Sex	0.086	**0.025**	0.942	0.159
Starter regime	0.243	0.890	0.835	0.202
Crown to rump length, cm	**0.021**	**0.005**	0.132	0.584
Snout to crown length, cm	0.084	**0.012**	0.434	**0.014**
Abdominal circumference, cm	**<0.001**	**0.001**	0.363	**0.041**
Cranial circumference, cm	**<0.001**	**0.006**	0.109	0.503
Body mass index[2], kg/m^2	**<0.001**	**0.040**	0.427	**0.032**
Ponderal index[3], kg/m^3	**0.001**	0.772	0.984	0.146
Birth weight: Cranial circumference, kg/cm	**<0.001**	**<0.001**	0.077	**0.009**
Snout to crown length: Birth weight, cm/kg	**<0.001**	**0.002**	0.057	0.201
Litter size pre-weaning[4]	0.776	**0.041**	0.445	0.055
Group size post-weaning[4]	0.863	0.784	0.389	0.545

[1] Relative birth weight = (Birth weight piglet/ mean birth weight birth litter)
[2] Body mass index = birth weight (kg)/[crown rump length (m)]^2
[3] Ponderal index = birth weight (kg)/[crown rump length (m)]^3
[4] Pre-weaning litter size/ group size post-weaning = [(total time (h) piglets reside within litter/ pen)/24 h]/ total period in d

than 1 and together explained 87.4% of the total variation: 57.9% principal component 1, 16.0% principal component 2, and 13.5% principal component 3. The majority of the piglets belonged to cluster 2 (61.9%), followed by cluster 3 (22.0%), and cluster 1 (16.1%) piglets. Cluster 1 piglets were born and weaned significantly lighter and differed to cluster 2 and 3 piglets with respect to various morphometric characteristics (e.g. CC, HL, BIW:CC and HL:BiW). Cluster 3 piglets had the highest birth weight, had a significantly ($P < 0.001$) higher BMI, PI, AC, and BiW:CC compared to cluster 2 piglets, but were weaned with a similar body weight ($P > 0.05$). Post-weaning mortality (d 28 to 61) did not differ between the different clusters ($P > 0.05$); with 10.9%, 5.21%, and 6.67% for respectively cluster 1, 2, and 3. However, cluster 1 piglets remained the lightest ($P < 0.001$; 35.3 kg, SD = 6.7) post-weaning, weighing 5 to 6.8 kg lighter at finisher compared to cluster 2 and 3 piglets (respectively 40.2 kg, SD = 7.2 and 42.1 kg, SD = 6.3). Although, cluster 3 piglets had a significantly lower pre-weaning ADG ($P = 0.027$) than cluster 2 piglets, at finisher cluster 3 piglets tended ($P = 0.073$) to weigh almost 2 kg heavier at finisher compared with cluster 2 piglets.

The majority of class 2 piglets (49.0%) were able to increase class at finisher, whereas the majority (41.6%) of weaning weight class 3 piglets decreased class between weaning weight and finisher weight. As a result, piglets of weaning weight class 2 had a higher probability to finish in finisher weight class 3 compared to weaning weight class 3 piglets (respectively 0.337, SD = 0.025 and 0.247, SD = 0.022, Figure 4.1c). Abdominal circumferences ($P = 0.010$), sex ($P = 0.017$), and pre-weaning ADG ($P = 0.011$) were significant in the final model for weaning weight class 2 piglets (Table 4.7). None of the morphometric characteristics were significant in the univariate models for weaning weight class 3 piglets and only relative birth weight appeared to be significant ($P = 0.028$). The final multifactorial model of weaning weight class 4 piglets consisted of BiW:CC ($P = 0.009$) only.

Table 4.12 Cluster characteristics of weaning weight class 1 piglets (smallest 25% at weaning) clustered in different groups based on birth weight, various morphometric characteristics, and pre-weaning growth. Data are expressed as LSM ± SED.[1]

Cluster (%)	**1** 16.1%	**2** 61.9%	**3** 22.0%	SED	Significance
Cluster characteristics					
Body weight, kg					
d 0	1.13[c]	1.26[b]	1.46[a]	0.007	<0.001
Relative birth weight[2]	0.795[c]	0.887[b]	0.988[a]	0.004	<0.001
d 28	3.91[b]	5.53[a]	5.54[a]	0.010	<0.001
Morphometric characteristics					
Abdominal circumferences, cm	20.0[b]	20.7[b]	22.0[a]	0.054	<0.001
Cranial circumferences, cm	20.0[c]	20.5[b]	21.3[a]	0.033	<0.001
Snout to crown length, cm	9.51[c]	9.75[b]	9.92[a]	0.015	<0.001
Crown rump length, cm	23.3[b]	24.5[a]	23.8[b]	0.049	<0.001
Body mass index[3], kg/m^2	20.2[b]	20.5[b]	25.6[a]	0.058	<0.001
Ponderal index[4], kg/m^3	86.5[b]	84.2[b]	108[a]	0.245	<0.001
Birth weight: Cranial circumferences, kg/cm	0.0553[c]	0.0607[b]	0.0683[a]	0.0003	<0.001
Snout to crown length: Birth weight, cm/ kg	9.23[c]	8.23[b]	7.09[a]	0.045	<0.001
Average daily gain, g/day					
d 0 – 28	99.5[c]	154[a]	147[b]	0.459	<0.001

[a,b,c] Values with different superscripts differ significantly ($P < 0.05$).
[1] Pigs were weighed within 12 h post-partum (d 0) and at weaning (d 27.7, SD = 1.1).
[2] Relative birth weight = (Birth weight piglet/ mean birth weight birth litter)
[3] Body mass index = birth weight (kg)/[crown rump length (m)]^2
[4] Ponderal index = birth weight (kg)/[crown rump length (m)

4.5 Discussion

Maximising sow reproductive potential via genetic selection for the total number of piglets born or weaned has resulted in increased litter sizes and thus the number of piglets weaned per sow per year (Koketsu et al., 2017). Although the number of piglets produced per sow per year is an important economic trait, as a result of limitations in the uterine capacity and maternal resources larger litter sizes increase the proportion of piglets born light (Foxcroft et al., 2006; Beaulieu et al., 2010a; Campos et al., 2012; Pardo et al., 2013), the number of intrauterine growth restricted (IUGR) piglets (Foxcroft et al., 2006) and consequently increase within-litter variation (Campos et al., 2012). To ensure that piglet quality and welfare is not compromised, pig producers are increasingly challenged to keep lightweight piglets alive and to improve weaning weight, minimising batch inefficiency. Knowing which piglets would benefit from intervention strategies at different stages of growth is important, as some lightweight pigs may be able to perform better without intervention, minimising variable growth rates within a group and possible economic losses. Although, recent research suggests that body shape at birth (e.g. BMI, AC) and not birth weight were able to predict postnatal growth of piglets born light (Douglas et al., 2016), research assessing the effect of body shape at birth together with well-known predictor variables such as birth weight, weaning weight and pre-weaning ADG on subsequent performance under commercial conditions is scarce. Our work is the first attempt that addresses these issues up to finishing stage. In addition, we have applied novel statistical methodologies to answer these questions. This allows us to make predictions about the effects of morphometric measurements on subsequent performance.

Furthermore, we investigated piglet ability for improved performance when given access to a nutrient enriched regime, i.e. with a higher essential amino acids: NE ratio, at weaning. Improved starter regimes tailored on the basis of lightweight piglet requirements rather than the average piglet, have been shown to be effective in improving post-weaning performance for pigs weaned light (Beaulieu et al., 2010b; Douglas et al., 2014a). The low feed intake (Nissen and Oksbjerg, 2011; Vieira et al., 2015), the lower serum concentrations of essential amino acids (He et al., 2016) and possible higher protein turnover (Thureen et al., 2003), suggest that lightweight piglets may benefit from an essential amino acids enriched diet. Piglets weaned light appear to have an immature digestive system (Cranwell et al., 1997; Pluske et al., 2003) and a higher epithelial cell turnover (Wiyaporn et al., 2013), and therefore may benefit from an increased supply of threonine (Le Floc'h et al., 2012) and methionine (Chen et al., 2014). Their lower ghrelin expression (Willemen et al., 2013) and serotonin concentrations (Willemen et al., 2014) suggest that an increased supplementation of tryptophan may stimulate appetite (Le Floc'h et al., 2012).

The results of our study did not support the hypothesis that piglets weaned light would improve performance when having access to a regime higher in essential amino acids. In the nutrient enriched regimes lysine was increased by 20% with the other essential amino acids being balanced to lysine, ensuring the appropriate ratios were maintained (NRC, 2012). Reasons for the lack of effect could be a result of: 1) lightweight pigs actually not having the hypothesised higher essential amino acids requirements post-weaning (Tokach, 2004), 2) lightweight piglets not having access to enough energy to use the extra essential amino acids supplied, and 3) an absence of a specific response to the supplemented amino acids, including their ratios to lysine. For example, there are suggestions that individual amino acids, such as arginine and glutamine (Roth, 2007), may enhance the growth of lightweight piglets. Although studies looking at infants that were born extremely light suggest that a more concentrated diet with increased levels of energy and amino acids accelerate weight gain (Moltu et al., 2014), others (Vieira et al., 2015) who have hypothesised that piglets weaned light would benefit from a more nutrient dense diet (i.e. different energy levels), were also unable to find a positive effect on the post-weaning performance. Nonetheless, the discrepancy amongst studies warrant further research assessing the effect of more concentrated diets on light piglet (birth and/ or weaning) post-weaning performances taking the different hypothesis of the lack of effect into consideration.

Birth (Quiniou et al., 2002; Calderón Díaz et al., 2017a) and weaning weight (de Grau et al., 2005; Paredes et al., 2012; Douglas et al., 2013; He et al., 2016) have been identified as predictors of post-weaning growth. Although, piglets born light (< 1.00 kg) have a higher mortality rate (Hales et al., 2013), a higher feed conversion ratio (Nissen and Oksbjerg, 2011) and need more time to reach market weight (Beaulieu et al., 2010a), one should discriminate between piglets that have been born light for gestational age e.g. ‘proportionally small’ (Foxcroft et al., 2006) and piglets that have suffered from growth restriction in utero. Different outcomes may be expected, with IUGR piglets believed to remain stunted throughout life (Wu et al., 2006). In addition, the severity of IUGR might vary between pigs and is suggested to be dependent on the stage of gestation and duration; the longer the period of growth restriction in utero the lesser the ability to recover post-partum (Wu et al., 2006).

Although piglets born light have a higher likelihood to remain light at weaning and finisher, our results suggest that not all lightweight pigs are the same and that some are actually able to do better than others. This is supported by the following: 1) pre-weaning ADG and not birth weight, was highly correlated with weaning weight, 2) body weight class change between birth and subsequent stages was under the influence of various morphometric characteristics (i.e. AC, CC, HL, CRL, PI, BMI, HL/BiW, BiW/CC), and 3) the multivariate analysis showed that relative birth weight and BMI were positively associated with pre-weaning growth for birth weight class 1 piglets rather than birth weight per se. Douglas et al (Douglas et al., 2016) have put forward several reasons why such morphometric measurements may be better predictors of postnatal performance. The positive association between BMI and pre-weaning ADG may be a result of: 1) differences in surface area: volume ratio (Amdi et al., 2013) influencing metabolic rate or 2) differences in the amount of maternal resources acquired during gestation important for development (Baxter et al., 2012; Alvarenga et al., 2013; Douglas et al., 2016). More specifically, piglets with a lower BMI but with the same birth weight as piglets with a higher BMI may have a higher metabolic rate this while the resources (e.g. colostrum, milk) are limited or a low BMI may suggest the piglet may have suffered from intrauterine malnutrition; both limiting piglets pre-weaning performance. Relative birth weight, on the other hand, may suggest that the lightest piglet of the litter might have been at a competitive disadvantage for colostrum intake (Declerck et al., 2016a).

In contrast to what has been previously found (Douglas et al., 2016), post-weaning ADG for birth weight class 1 pigs was positively associated with weaning weight and head shape at birth (i.e. BiW:CC), with the absence of weaning weight in the previous study (Douglas et al., 2016) most likely have contributed to the differences seen. The positive association between BiW:CC and post-weaning performance suggests that pigs with a larger head size in relation to birth weight (low BiW:CC) have an impaired post-weaning performance. The dolphin-like forehead, the adaptive brain sparing effect as a result of placental insufficiency, has been used for the identification of IUGR piglets (Hales et al., 2013): piglets that might not be able to display normal growth and remain stunted throughout life (Amdi et al., 2013). Also in our study BiW:CC discriminated between piglets that suffered from a certain degree of IUGR. The latter hypothesis warrant further research in which a differentiation should be made between light piglets on the basis of head morphology at birth testing piglets ability to reach similar pre- and post-weaning performances (IUGR vs. small with a normal head shape). On the other hand, these findings also emphasize the importance of weaning weight: a good start is essential and increasing body weight class pre-weaning has been shown beneficial for subsequent performance. Weaning weight does not only influence subsequent performance (de Grau et al., 2005; Paredes et al., 2012; Douglas et al., 2013; He et al., 2016), with a higher likelihood for a slower post-weaning growth rate for weaning weight class 1 (bottom 12.5 % at weaning) compared to birth weight class 1 pigs (bottom 12.5 % at birth) (Douglas et al., 2013), but is also an important factor influencing disease risks (Calderón Díaz et al., 2017b) and batch efficiency in all-in-all-out systems, especially for pig enterprises from the bottom quartile (Magowan et al., 2007). This suggests that the emphasis should be on the pre-weaning management (Deen and Bilkei, 2004; Miller et al., 2012; Declerck et al., 2016a; Huting et al., 2017) for improving the performance of piglets born light. At the same time our results point towards which piglets are most likely to benefit from such sometimes time consuming and expensive strategies.

There are several reasons why a piglet born heavy might end up light at weaning, such as: direct and indirect competition for milk intake (Huting et al., 2017) and sickness. In our experiment 51.9 % of piglets born heavy (e.g. birth weight class 2 to 4) fell into this category. However, such piglets were still at an advantage for compensatory growth post-weaning, having a higher OR to end up heavy at finisher, compared to piglets born and weaned light. Compensatory growth after a period of stunting has previously been shown for piglets born heavier once having access to an better quality starter regime (Douglas et al., 2014b). However, differences in pre-weaning nutrient intake might have set appetite during subsequent stages (Hales and Barker, 2001) and therefore piglets with a poor pre-weaning ADG achieve a lower growth potential than similar sized piglets with a greater pre-weaning ADG.

In addition, the multivariate and cluster analysis emphasised that not all piglets weaned light are the same: the distinction between piglets weaned light that can or cannot exhibit compensatory growth was not under the influence of birth weight only. Our data suggest that piglets born and weaned light and born disproportional (cluster 1), were unable to improve performance under the commercial conditions of our experiment. Piglets of cluster 2 and 3, on the other hand, were weaned relatively heavier but differed from one another with respect to body shape at birth, with cluster 3 piglets having a greater post-weaning growth than cluster 2 piglets that were born lighter and relatively disproportional. The multivariate analysis for weaning weight class 1 piglets, on the other hand, showed that post-weaning performance was not under the influence of birth weight, but similarly to birth weight class 1 piglets were positively associated with weaning weight, and several morphometric characteristics i.e. PI and head shape at birth (BiW:CC). These morphometric characteristics (Amdi et al., 2013; Hales et al., 2013) may differentiate between pigs that have suffered from a certain degree of IUGR as discussed previously. Piglets that are born disproportional (e.g. low BiW:CC and PI) and weaned light may benefit from specialised strategies post-weaning. However, more research is necessary to determine whether these piglets can compensate when having access to an improved post-weaning environment or whether they remain stunted.

4.6 Conclusion

This study suggests that a subset of piglets born lightweight are able to show compensatory growth. These are piglets that are characterised by a higher BMI and a higher relative birth weight, the relatively bigger piglets of the litter. Treating all lightweight pigs the same pre-weaning might explain why management strategies commonly applied are able to induce an improved performance, but are less likely to reduce litter CV. Piglets that are born long and thin (low BMI), on the other hand, would most likely benefit from pre-weaning intervention strategies. Post-weaning strategies should focus on pigs that are born disproportional (low PI and low BiW:CC) and on those weaned light. In other words, the results of the present study suggest that pig producers should discriminate between pigs that are weaned light on the basis of their birth characteristics to better target the often costly and time consuming intervention strategies, for example by ear-tagging the affected piglets at birth. In addition, researchers assessing the effect of post-weaning strategies on piglets weaned light should take caution when selecting piglets on the basis of weaning weight only, as piglet shape at birth might influence the experimental outcomes. In this study we were unable to demonstrate any benefits arising from the nutritional manipulation of the nursery feeding regime on the lightweight piglets; all classes of lightweight piglets were unable to improve post-weaning performance when having access to the nutrient enriched regime (higher essential amino acids: NE ratio), which may suggest that lightweight piglets do not have higher essential amino acids requirements.

Chapter 5.

Weaning age and post-weaning nursery feeding regime are both important in improving the performance of lightweight pigs

5.1 Abstract

The aim was to investigate the effect of weaning age, weaning weight and nursery feeding regime on post-weaning performance. The focus was on pigs weaned light, as they may be better off when weaned at a later age and/or offered a specialist nursery feeding regime. Piglets (n = 1448) from one farrowing batch of 110 sows that farrowed over 2 weeks, were individually weighed and their morphometric measurements were taken at birth. Pigs were weaned on the same day, but variation in date of birth resulted in variable weaning ages (mean age d 34.1, SD = 2.5). The youngest 50% were classified young and the oldest 50% as old; within an age class, the lightest 50% were classified light, the heaviest 50% as heavy, and housed accordingly. Pigs were individually weighed at weaning, 7- and 15-weeks post-weaning. At weaning young pigs were 6 d younger and 1.4 kg lighter than old pigs, whereas light pigs were 3.2 kg lighter than heavy pigs. Pigs were randomly allocated to a 3-stage superior or control nursery feeding regime with superior pigs having a 65% greater allowance (on a kg/pig basis) of the first and second stage feeds than the control. Pigs weaned young had a higher mortality rate (P = 0.046) from weaning to 7-weeks post-weaning than pigs weaned old (9.14 vs. 4.98%). As expected, age and weight significantly (P < 0.001) affected performance to both at 7 and 15-weeks post-weaning: at 15-weeks pigs weaned young were 5.5 kg lighter than pigs weaned old; pigs weaned light were 9.0 kg lighter than heavy pigs. It was estimated that pigs weaned young and light needed ~4 d more (P = 0.018) to reach 60 kg body weight than pigs weaned old and light. Feed intake was not affected by regime, age and weight, or their interactions. Performance was not affected by feeding regime (P > 0.05), but was affected by the weight × feeding regime interaction (P < 0.05) to 7-weeks post-weaning light pigs on the superior feeding regime were 1.2 kg heavier than light pigs on the control feeding regime; this was not the case for the heavy pigs. Similar results were seen when pig performance was estimated to a common body weight (birth to 20 kg), although the above interaction was no longer significant by 60 kg body weight. Post-weaning performance up to 7-weeks post-weaning were positively associated with birth weight to cranial circumference ratios and weaning weight (P < 0.05) for both young and light and old and light pigs; whereas for old and light pigs additional predictors were weaning age (P = 0.044) and feeding regime (P = 0.027). Improved growth for light pigs up to 7 weeks post-weaning could be obtained by a greater allowance of the nursery diets. However, weaned at a

later age benefitted performance of light pigs to a common body weight, suggesting that this might be a more beneficial strategy with long term benefits.

5.2 Introduction

The management of lightweight piglets, which have become more common with the increase in the litter size of modern sow genotypes, remains a challenge (Ocepek et al., 2017). Post-weaning, these pigs have a higher mortality risk, grow slower and consequently need more time to reach slaughter weight (Collins et al., 2017). Farmers try to manage this challenge by either offering lightweight pigs a specialist nursery feeding regime (e.g. starter diets using readily digestible/ high quality nutrient sources, synthetic amino acids, and palatable ingredients making it more nutrient dense) (Beaulieu et al., 2010b; Collins et al., 2017), or by weaning them at a later stage, e.g. by 'split weaning' (Pluske and Williams, 1996; Vesseur et al., 1997; Abraham et al., 2004), which involves weaning the heavier piglets and leaving the lightweight piglets on the sow for a longer period of time.

There are good reasons why either of the above strategies, or their combination, might work. Lightweight pigs have a more immature digestive system (Cranwell et al., 1997; Pluske et al., 2003) and a lower feed intake post-weaning (Magowan et al., 2011a) than heavyweight pigs. Prolonging milk intake may enhance gut maturity (Fanaro et al., 2003; Schack-Nielsen and Michaelsen, 2007), thus reducing post-weaning growth check. In addition, lightweight pigs may have different nutrient requirements as a result of differences in gut maturity compared with heavy pigs of the same age. Previous research has suggested that feeding lightweight pigs for a longer period of time on a specialist nursery feeding regime, may influence their subsequent performance (Magowan et al., 2011a; Douglas et al., 2014a). Usually these effects have been investigated only on the basis of weaning weight, without considering weaning age and the interactions between the two.

Because both strategies for managing lightweight pigs are associated with significant costs and disruption of the flow of pigs from a batch, it is imperative to know what their consequences on the long term performance and their financial implications would be. The objectives of this experiment were to investigate: 1) the consequences of delayed weaning, increased allowance (on a kg/pig basis) of nursery feeding regimes and their combination on the performance of lightweight pigs to slaughter; and 2) whether all lightweight pigs are able to benefit equally from the above strategies. We have previously shown that not all lightweight pigs are alike and that the ones less likely to catch up growth post-weaning are those weaned light and disproportional, i.e. piglets born long and thin and/or with a greater head circumferences in relation to birth weight (Douglas et al., 2016; Huting et al., 2018). The latter, may be related to intrauterine growth restriction (IUGR) which is often characterised by a dolphin-like forehead (Amdi et al., 2013). Here, we investigated whether these morphometric predictors interact with the management of lightweight piglets, i.e. the time of weaning and the allowance of the nursery regime.

5.3 Materials and methods

5.3.1 *Experimental design*

The design was a 2x2x2 factorial with two ages (young vs. old), two weaning weights (light vs. heavy) and two nursery feeding regime regimes (control vs. superior) as post-weaning treatments. The experiment took place on a Large White x Landrace sow, farrow-to-finish commercial farm in Great Britain from February 2017 till July 2017 and the experiment was approved by the Animal Welfare and Ethical Review Body (AWERB project ID no. 419) of Newcastle University. Due to limitations in the availability of the farm piglets (n = 1448) born in a single farrowing batch were followed from birth to 15-weeks post-weaning. The study was sponsored by AHDB (Agriculture and Horticulture Development Board) Pork and Primary Diets.

5.3.2 *Animals, housing, and management*

The farrowing batch consisted of 110 sows of different parities: 22 gilts and 88 sows (mean parity 4.38, SD = 2.39; parity range 2-13). Sows and gilts were placed in farrowing pens (2.7 x 1.8 m) with a crate and a heated creep area (floor heating) and farrowed over a 2-week period. The majority of cross-fostering took place within the first 4 days of life to standardize litter sizes to the number of functional teats and to create litter uniformity (AHDB Pork, 2017a). Fourteen sows (12.7%) were weaned shortly after birth and were replaced by other sows due to space restrictions or poor performance. The latter resulted in that 53.9% of the piglets were eventually cross-fostered. Piglets had *ad libitum* access to a 2-phase pelleted creep feed regime provided in a hopper from 10 days of age (d 9.78, SD = 1.67) to weaning; diet 1 of the nursery feeding regime (22.0 % CP, 10.4 MJ NE/kg diet) was provided during the last week prior to weaning (see Table 5.1 for diet specifications).

All pigs were weaned on the same day at a mean age of 34.1 d (SD = 2.5), irrespectively of their date of birth. At weaning, pigs were moved to the fully slatted weaner facilities making groups of 60 pigs/pen (5.25 x 3.35 m) with stocking density consistent with UK legislations.

Pigs were grouped on the basis of their weaning age, weaning weight, and nursery feeding regime. Pigs were fed using an automatic rationed liquid feeding system with one feeder per pen pair. Pigs remained in the same group and room up to 7-weeks post-weaning; thereafter pigs were mixed to create smaller groups depending on the pen size (range 20 – 35 pigs/ pen) ensuring a similar stocking density between pens and moved to one of the 3 fully slatted finisher rooms on site. How this was accounted for the in final model for the performance parameters from 7 weeks to 15 weeks post-weaning is described in section 5.3.4.

5.3.3 *Experimental procedures*

Pre-weaning performance. Piglets were individually weighed to the nearest 1 g within 12 - 24 h after birth. At the same time, additional morphometric measurements were taken and piglets were individually ear tagged (Dentag, Toptags, Kelso, UK) for identification purposes. The morphometric measurements taken from each individual piglet were: crown to rump length (CRL, cm), snout to crown length (head length HL, cm), abdominal circumferences (AC, cm) taken at the anterior side of the umbilicus, and cranial circumferences (CC, cm). Additional variables were created, such as ponderal index (PI; birth weight, kg/CRL, m^3), body mass index (BMI; birth weight, kg/CRL, m^2), birth weight: cranial circumferences (BiW:CC, kg/cm), and snout to crown length: birth weight (HL:BiW, cm/kg) (Douglas et al., 2016; Huting et al., 2018). In addition, piglet individual birth weight was expressed in relation to birth litter average (Relative birth weight) by dividing piglet birth weight by the mean birth weight of the birth litter (Paredes et al., 2012; Huting et al., 2018) as it appeared to be an important parameter influencing light piglets pre-weaning performance (Huting et al., 2018).

From the piglets that died pre-weaning, additional recordings were taken where possible, including the cause of death (e.g. non-viable, starvation, anaemic, crushed, savaging, meningitis and diarrhoea), body weight and foster sow. Piglets were retagged (Suretag flag, Dalton tags, Newark Nottinghamshire, UK) at 20.7 (SD = 2.8) days of age. All pigs were weaned on a Thursday morning (d 34.1, SD = 2.5), but piglets were individually weighed 2 to 3 days prior to weaning (31.7, SD = 2.6); this was done pseudo randomly, to spread the workload and enable allocation to treatments. Piglets were given an oral suspension of Baycox (Bayer plc, Reading, UK) at d 3-5 of life (d 3.89, SD = 1.45). At the same time, litter details (sow identification number, piglet identification number) were recorded, as by this time the majority of cross-fostering had taken place.

Table 5.1 Ingredient composition, on an as-fed basis, and chemical analysis of the post-weaner feeds used. Pigs were randomly allocated to either a high feed allowance (superior) or a control nursery regime. All diets were identical between the two feed allowances. However, pigs fed the superior regime had a 65% greater allowance of the first and second stage feeds before moving to the grower regime.[1]

Diet	1	2
Ingredient g/kg		
Micronized barley	150	50.0
Wheat	218	450
Micronized wheat	50.0	50.0
Micronized oats	100	-
Fishmeal	72.5	25.0
Soya Hypro	127	210
Full fat soybean	30.0	25.0
Pig weaner vitamin/ trace element supplement[2]	5.00	5.00
Dried skim milk powder	40	-
Whey	146	34.7
L-Lysine HCL	3.17	4.93
DL-Methionine	1.98	2.12
L-Threonine	1.91	2.39
L-Tryptophan	0.38	0.24
L-Valine	0.70	1.28
Pan-Tek Robust CB	0.15	0.15
Sucram	0.10	0.10
Benzoic acid	5.00	5.00
Limestone flour	1.79	-
Dicalcium phosphate	6.19	15.1
Salt	-	
Binder (LignoBond DD)[3]		4.17
Sodium bicarbonate		3.57
Soya oil	28.2	11.0
Analysed composition, % as fed		
CP	22.1	20.2
Crude fibre	2.10	2.40
Moisture	9.70	11.2
Ash	5.70	6.20
Calculated composition, % as fed or as specified		
NE, MJ/kg	10.4	9.39
Calcium	0.75	0.71
Phosphorus	0.68	0.68
Lactose	12.5	2.50
Lys	1.54	1.40
SID Lys[4]	1.40	1.28
Met	0.61	0.52

[1] Diets were supplied by Primary Diets, ABAgri, Ripon, North Yorkshire, United Kingdom
[2] It provided per kilogram of complete diet 11,500 IU of vitamin A, 2,000 IU of vitamin D_3, 100 IU of vitamin E, 4 mg of Vitamin K, 27.5 µg of vitamin B_{12}, 15 mg of pantothenic acid, 25 mg of nicotinic acid, 150 µg of biotin, 1.0 mg of folic acid, 160 mg of Cu ($CuSO_4$), 1.0 mg of iodine ($Ca(IO_3)_2$), 150 mg of Fe ($FeSO_4$), 40 mg of Mn (MnO), 0.25 mg of Se (bone morphogenetic protein), and 110 mg Zn ($ZnSO_4$).
[3] Borregaard LignoTech, Sarpsborg, Norway.
[4] SID = standardized ileal digestible

Nursery feeding regime. The 3-phase nursery feeding regime (Primary Diets, ABAgri, Ripon, North Yorkshire, UK) compromising of diet 1 (22.0 % CP, 10.4 MJ NE/kg feed), diet 2 (20.2 % CP, 9.39 MJ NE/kg feed) and a 'grower' diet were fed from weaning to 7-weeks post-weaning, a 'finisher' diet was fed between 7- and 15-weeks post-weaning. All diets (Table 5.1), including the grower and finisher diet, met or exceeded the nutrient requirements for pigs of this size and age (NRC, 2012) and were identical between the experimental treatments. However diet 1 and diet 2 were fed in different quantities. Pigs allocated to the higher nursery allowance (superior) regime were fed a 65% greater allowance of diet 1 and diet 2 (3.80 kg/pig and 3.33 kg/pig respectively) compared with pigs allocated to the control regime (2.30 kg/pig and 2.00 kg/pig respectively). After this, an extra 2 kg of diet 2 was mixed with the grower diet to ease diet transition of both the control and superior pigs. The pigs were fed *ad libitum* until they consumed the amount of feed allowance they were allocated to. The amounts of feed in the control regime were based on the normal feeding strategy of the pig unit. The difference between the two regimes was set to 65% to ensure the economic viability of the superior regime; which was around 50% more expensive per pig compared with the control regime ($6.84 vs. $4.62 per pig).

The cost of the feeds (£/ton June 2018; exchange rate June 2018 £1 = US$1.33) was provided by the feed company; diet 1 (£ 688/ ton, $ 915/ ton), diet 2 (£ 474/ ton, $ 630/ ton) and grower diet (£240/ ton, $ 319/ ton). This was used to calculate the following; 1) total feed cost per pig, 2) total cost per kilogram gained (weaning to 7-weeks post-weaning), and 3) the margin over feed (MOF) (as per Douglas et al., 2014a):

$$MOF = [(Gain_{kg} \times Prop_{carcass}) \times Price_{kgcarcass}] - Total_{feedcost}$$

Where $Gain_{kg}$ is the kilogram gain between weaning to 7-weeks post-weaning, $Prop_{carcass}$ the proportion of carcass weight from live weight (0.75), $Price_{kgcarcass}$ the price per kilogram carcass weight (as of June 2018, $2.62; AHDB Pork), and $Total_{feedcost}$ the total feed cost per pig.

Post-weaning performance. A total of 960 pigs were selected from 1135 healthy (e.g. free from lameness, viable, > 4 kg) individuals available at weaning. On the basis of weaning age, pigs were split into two groups: the bottom 50% were classified young (< mean weaning age; d 32.4, SD = 0.3) and the rest classified as old (> mean weaning age; d 35.9, SD = 0.3). Within a weaning age class, the lightest 50% (≤ mean weaning weight for young or old) were classified light, the heaviest 50% pigs (> mean weaning weight for young or old) were classified heavy. The latter was done between pigs of the same date of birth. It should be noted however that a significant proportion of pigs was born on the same day and weaned at d 34 (n = 329). As the experiment had the aim to access the effect of weaning age on post-weaning performance and therefore a significant difference between the weaning age of pigs weaned young and old should be obtained, the pigs weaned at d 34 were excluded from the majority of the analysis (except for feed intake) resulting in young pigs being weaned at 31.8 (SD = 0.2) d of age and old pigs being weaned at 37.5 (SD = 0.3) d of age (see section 5.3.4 for more details). Nevertheless, the pigs weaned at d 34 had to be included in this experiment to standardize stocking density consistent with UK legislations across the different treatments.

The day before weaning (Wednesday) pigs were marked using different coloured markers (MS marking spray, MS Schippers, Bladel, The Netherlands) and different markings indicating their post-weaning treatments (age, weight, and nursery feeding regime) on the following morning (Thursday). On the basis of the age and weight classes, pigs were pseudo randomly allocated to one of the two different nursery feeding regimes; superior or control, balancing for weaning age, weaning weight and sex and making groups of 120 pigs per treatment group. Each of the 8 treatment group consisted of two parallel pens (~60 pigs per pen) that shared one feeder.

Feed intake was recorded on a weekly basis per pen pair. Irrespective of weaning age, pen weights were taken at 1-, 3-, 4-, and 5-weeks post-weaning using a platform weighing scale. Individual body weights were taken at 2-, 7-, and 15-weeks post-weaning, 1 week before the biggest pigs of the batch were sent to slaughter, after which the trial finished.

5.3.4 *Statistical analysis*

The effects of weaning weight, weaning age and nursery feeding regime and their interactions on post-weaning performance were evaluated using the PROC MIXED procedure of SAS version 9.4 (SAS Inst. Inc. Cary, NC). The residual variance of the data was tested for normality using the UNIVARIATE procedure. Data were expressed as least square means (LSM), with approximate standard errors of the differences of means (SED) unless stated otherwise. Statistical significance was assessed at the 5% level and tendencies were set at 10%. Several covariance structures were tested, but variance components resulted in the lowest AIC (Akaike Information Criteria) and was selected for the final model.

Post-weaning performance. Post-weaning mortality was evaluated with a chi-square test. The experimental unit between weaning and 7-weeks post-weaning was pen mean nested within pen pair and was analysed in two ways: 1) including all 120 pigs/ treatment, and 2) excluding pigs that were weaned at d 34 (see below). As only one feeder was available per treatment, the experimental unit for feed intake and MOF was pen pair. As a result of mortality and pig removals due to illness, post-weaning average daily feed intake (FI) was corrected using the following formula over a given period:

$$FI = (Total_{intake}) / (Time_{pig} / 24\ h)$$

With $Total_{intake}$ the total amount consumed/ pen pair (g) and $Time_{pig}$ the total time pigs reside in the pen (h).

Only individual pig data (i.e. 2-3 days prior at weaning, 2-, 7-, and 15-weeks post-weaning) could be used for the analysis in where the intermediate pigs (pigs weaned at d 34) were excluded. The experimental unit was pen mean. Pen means were based on the number of young or old pigs that were in the pen. A WEIGHT statement was used to account for differences in the number of pigs/ treatment on which the average was based. The homogeneity of variance was tested using the Levene's test (HOVTEST) and graphical diagnostics in PROC GLM. Where data were unbalanced, the denominator degrees-of-freedom (DDF) Satterthwaite was used for adjusting the degrees of freedom to unequal variance and studentized maximum modulus (SMM) for multiple comparisons, in all other cases protected difference (PDIFF) was used to compare means. Since pigs were mixed after 7-weeks post-weaning, the subsequent experimental unit was pen mean for each constituent treatment group, based on the number of young and light, young and heavy, old and light and old and heavy within each pen, taking post-weaning nursery feeding regime into consideration. The pen means were blocked by pen nested within finisher room. A WEIGHT statement was used to account for the difference in the number of pigs the pen mean was based on. For both models (i.e. weaning to 7-weeks post-weaning and 7- to 15-weeks post-weaning) adjusted group size (i.e. adjusting for mortality) was added to the model as covariate:

$$Group\ size = (Time_{pig} / 24\ h) / Time_{total}$$

With $Time_{pig}$ the total time (h) pigs reside in the pen and $Time_{total}$ the total period (d). A WEIGHT statement was used to account for differences in the number of pigs/ treatment the average was based on.

Performance to 20 and 60 kg. The performance of the pigs from birth and weaning to a common weight (i.e. 20 and 60 kg) was also investigated. Twenty kg was chosen because it was the weight of the lightest pig within the cohort at 7-weeks post-weaning, whereas the second one the lightest pig at 15 weeks post-weaning. The data were analysed using the PROC MIXED models as stated previously.

Predictor variables for post-weaning performance. We have previously shown that not all lightweight pigs are alike and that the effectiveness of post-weaning strategies may be dependent on piglets shape at birth (Douglas et al., 2016; Huting et al., 2018). The experimental unit for both models (i.e. univariate and multivariate) was pig blocked by pen nested within pen pair. All potential predictor variables (i.e. birth weight, total number of born, morphometric characteristics, relative birth weight, sex, pre-weaning litter size, weaning age, weaning weight, pre-weaning ADG, and nursery feeding regime) and their effect on post-weaning performance of pigs of the different age and weight classes (i.e. young and light, young and heavy, old and light, and old and heavy) excluding the intermediate pigs were fitted in a univariate mixed model (PROC MIXED); those that were significant ($P < 0.05$) were taken forward in the multivariate analysis. Different multivariate models were built following a forward and backward stepwise procedure for variables that were highly correlated ($r > 0.70$; PROC CORR), using the AIC criteria (the smaller the better) to determine the model of best fit. Only factors with a probability below 0.05 were retained in the final model. The experimental unit for both models (i.e. univariate and multivariate) was pig blocked by pen nested within pen pair.

5.4 Results

Pre-weaning performance. The average number of piglets born alive was 13.7 (range 2 to 21) with an average birth weight of 1.49 kg (SD = 0.30) and birth litter CV of 19.5 (SD = 7.0). Average litter size at 2-3 days prior to weaning was 12.4 (SD = 1.9) with an average weaning weight and ADG of 9.01 kg (SD = 1.63) and 237 g/day (SD = 43) respectively. Pre-weaning mortality rate of piglets born alive was 17.2%, of which 25.3% was attributed to crushing.

Post-weaning performance. The number of pigs per treatment after the ‘intermediate’ pigs were excluded from the analysis and overall mortality rate can be found in Table 5.2. Table 5.3 shows the effect of age, weight, and nursery feeding regime on post-weaning performance of all pigs. Table 5.4 shows the same information but without the pigs weaned at d 34. Since the results are similar between Table 5.3 and Table 5.4, only results of Table 5.4 are discussed here. A total of 188 pigs were considered young and light, 162 pigs were considered young and heavy, 145 pigs were considered old and light, and 136 pigs were considered old and heavy (Table 5.2). Post weaning mortality was not significantly ($P > 0.05$) affected by weaning weight or nursery feeding regime. Pigs weaned young (d 31.8, SD = 0.2), however, had a significantly

Table 5.2 The number of pigs and mortality rate per treatment (i.e. weaning age, weaning weight and nursery regime) during the different stages (post-weaning) of production, excluding pigs weaned at an intermediate age (d 34). At weaning, pigs were split into 2 groups based on their weaning age: the bottom 50% were classified 'young' and the upper 50% were classified 'old'; within age class the lightest 50% were classified 'light', the heaviest 50% classified 'heavy'. Pigs were randomly allocated to the dietary treatment: either fed a high feed allowance regime (superior) in which pigs had a 65% greater allowance of the first and second stage feeds or the control regime.[1]

Weaning age	Young		Young		Old		Old		Total		Total		Total	
Weaning weight	Light	Light	Heavy	Heavy	Light	Light	Heavy	Heavy	Young	Old	Light	Heavy	Superior	Control
Regime	Superior	Control	Superior	Control	Superior	Control	Superior	Control						
Number of pigs														
Weaning	92	96	79	83	71	74	68	68	350^{a}	281^{b}	333^{a}	298^{b}	310	321
Week 2 post-weaning	92	96	76	82	68	72	68	68	346^{a}	275^{b}	327^{A}	294^{B}	303	318
Week 7 post-weaning	88	95	75	79	68	69	68	68	337^{a}	273^{b}	320^{A}	290^{B}	299	311
Week 15 post-weaning	84	86	75	73	67	69	65	66	318^{a}	267^{b}	306	279	291	294
Mortality rate, %														
Total	8 (8.70%)	10 (10.4%)	4 (5.06%)	10 (12.0%)	4 (5.63%)	5 (6.76%)	3 (4.41%)	2 (2.94%)	32^{a} (9.14%)	14^{b} (4.98%)	27 (8.11%)	19 (6.38%)	19 (6.13%)	27 (8.41%)

^{a,b} Numbers with different superscripts differ significantly ($P < 0.05$)

^{A,B} Numbers with different superscripts tended to differ ($P < 0.10$)

[1] At weaning, pigs were split into 2 groups based on their age excluding pigs that were weaned at d 34: the bottom 50% were classified young and the upper 50% were classified old. Within weaning age group pigs were classified light or heavy on the basis of their weaning weight.

Table 5.3 The effect of weaning age, weaning weight, and nursery feeding regime on post-weaning performance**.** At weaning, pigs were split into 2 groups based on their weaning age: the bottom 50% were classified young and the upper 50% were classified old. Within weaning age group pigs were classified light (bottom 50%) or heavy (upper 50%) on the basis of their weaning weight. Pigs were then randomly allocated to the nursery feeding regime treatment: either fed a high feed allowance regime (superior) or the control regime. All diets were identical between the two feed allowances; however pigs fed the superior regime had a 65% greater allowance of the first and second stage feeds.[1]

Weaning age (A)	Young		Young		Old		Old									
Weaning weight (W)	Light	Light	Heavy	Heavy	Light	Light	Heavy	Heavy		Significance[2]						
Nursery feeding regime (R)	Superior	Control	Superior	Control	Superior	Control	Superior	Control	SED	A	W	R	A×W	W×R	A×R	A×W×R
Age, days																
Weaning	32.2	32.2	32.5	32.5	36.0	36.1	35.8	35.9	0.418	<0.001	0.654	0.779	0.114	0.953	0.564	0.928
Body weight, kg																
Weaning weight	6.65	6.65	10.2	10.2	7.81	7.87	11.8	11.9	0.180	<0.001	<0.001	0.527	0.008	0.521	0.369	0.650
Week 1 post-weaning	8.92	9.04	12.5	11.9	9.76	10.7	13.5	13.3	0.412	<0.001	<0.001	0.795	0.995	0.014	0.091	0.501
Week 2 post-weaning	12.5	12.8	16.6	18.1	13.7	14.4	18.4	18.1	0.815	0.003	<0.001	0.106	0.351	0.931	0.256	0.099
Week 3 post-weaning	15.6	14.5	18.7	18.8	17.9	17.3	22.3	22.5	0.605	<0.001	<0.001	0.112	0.055	0.045	0.480	0.567
Week 4 post-weaning	21.0	20.3	25.7	25.5	23.4	22.7	27.9	28.1	0.987	<0.001	<0.001	0.297	0.910	0.364	0.712	0.777
Week 5 post-weaning	25.9	25.2	32.1	30.8	28.7	28.7	32.1	32.9	0.884	<0.001	<0.001	0.357	0.014	0.865	0.068	0.365
Week 7 post-weaning	34.3	33.8	40.1	41.0	38.0	37.1	42.7	43.6	0.782	<0.001	<0.001	0.727	0.167	0.024	0.845	0.741
Week 15 post-weaning	89.3	89.2	98.5	99.0	93.0	93.6	102	103	1.14	<0.001	<0.001	0.639	0.729	0.839	0.810	0.789
ADG, g/day																
Weaning - Week 2 post-weaning	348	368	389	479	359	394	406	374	44.5	0.440	0.022	0.107	0.083	0.974	0.129	0.062
Weaning – Week 7 post-weaning	524	516	570	587	572	556	591	605	13.2	0.001	<0.001	0.737	0.053	0.031	0.541	0.790
Week 2 – Week 7 post-weaning	606	585	641	634	667	627	675	709	21.2	<0.001	<0.001	0.198	0.834	0.041	0.332	0.043
Week 7 – Week 15 post-weaning	920	929	974	965	924	952	1010	982	14.6	0.046	<0.001	0.986	0.487	0.066	0.986	0.339
CV																
Weaning weight	17.5	18.0	11.2	11.6	16.5	19.3	12.3	11.8	1.14	0.623	<0.001	0.327	0.776	0.294	0.668	0.323
Week 2 post-weaning	17.8	17.6	12.3	14.4	19.0	24.6	17.4	13.4	2.07	0.066	0.006	0.541	0.506	0.221	0.973	0.065
Week 7 post-weaning	14.9	16.5	12.1	12.2	16.6	18.2	12.5	11.7	1.13	0.296	<0.001	0.447	0.268	0.240	0.748	0.746

[1] Individual body weights were taken at 2 – 3 days (d 31.7, SD = 2) prior to weaning (d 34.1, SD = 1.9), 2-, 7- and 15-weeks post-weaning (d 144, SD = 2). During the other time points, pen weights were taken.

[2] The experimental unit for all models was pen mean with main effects of interest: weaning age (A), weaning weight (W), nursery regime (R), and their interactions: A × W, W × R, A × R, A × W × R. A weight statement was used to account for differences in the number of pigs on which the pen means were based. From weaning to 7-weeks post-weaning pigs remained in the same group and pen pair was used as a random factor. From 7-weeks post-weaning to finisher pigs were mixed in smaller groups, therefore pen mean nested within the room was used as a random factor. Adjusted group size was inserted as covariate to all models

Table 5.4 The effect of weaning age, weaning weight and nursery feeding regime on post-weaning performance excluding pigs weaned at an intermediate age (d 34). At weaning, pigs were split into 2 groups based on their age excluding pigs that were weaned at d 34: the bottom 50% were classified young and the upper 50% were classified old. Within weaning age group pigs were classified light or heavy on the basis of their weaning weight. Pigs were then randomly allocated to the different pens and nursery feeding regime: either fed a high feed allowance regime (superior) or the control regime. All diets were identical between the two feed allowances; however pigs fed the superior regime were fed a 65% greater allowance of the first and second stage feeds.[1]

Weaning age (A)	Young		Young		Old		Old									
Weaning weight (W)	Light	Light	Heavy	Heavy	Light	Light	Heavy	Heavy		Significance[2]						
Nursery feeding regime (R)	Superior	Control	Superior	Control	Superior	Control	Superior	Control	SED	A	W	R	A×W	W×R	A×R	A×W×R
Age, days																
Weaning	31.7	31.7	31.9	31.9	37.5	37.6	37.4	37.4	0.430	<0.001	0.897	0.824	0.353	0.970	0.849	0.903
Body weight, kg																
Weaning	6.93	6.89	10.1	10.1	8.27	8.37	11.5	11.5	0.250	<0.001	<0.001	0.754	0.962	0.980	0.501	0.945
Week 2 post-weaning	12.8	13.0	16.4	18.0	14.5	15.4	18.2	17.9	1.04	0.004	<0.001	0.129	0.156	0.849	0.435	0.113
Week 7 post-weaning	35.3	34.1	39.5	40.9	40.0	38.7	43.0	43.8	1.30	<0.001	<0.001	0.889	0.171	0.044	0.673	0.815
Week 15 post-weaning	91.0	89.8	98.2	98.4	96.4	94.8	104	104	1.35	<0.001	<0.001	0.527	0.752	0.380	0.908	0.990
ADG, g/day																
Weaning - Week 2 post-weaning	353	370	380	485	375	421	411	387	55.9	0.955	0.108	0.108	0.116	0.820	0.241	0.081
Weaning – Week 7 post-weaning	535	519	558	587	602	576	604	615	24.0	0.001	0.005	0.937	0.185	0.046	0.435	0.816
Week 2 – Week 7 post-weaning	620	587	640	632	701	643	690	718	29.8	0.001	0.016	0.130	0.997	0.034	0.811	0.182
Week 7 – Week 15 post-weaning	929	931	986	954	944	952	1034	1006	16.2	0.004	<0.001	0.242	0.154	0.121	0.826	0.949

[1] Individual body weights were taken at 2 – 3 days (d 31.7, SD = 2.6) prior to weaning (d 34.6, SD = 3.0), 2-, 7-, and 15-weeks post-weaning (d 144, SD = 2).

[2] The experimental unit for all models was pen mean with main effects of interest: weaning age (A), weaning weight (W), nursery regime (R), and their interactions: A × W, W × R, A × R, A × W × R. A weight statement was used to account for differences in the number of pigs on which the pen means were based. From weaning to 7 weeks post-weaning pigs remained in the same group and pen pair was used as a random factor. From 7 weeks post-weaning to finisher pigs were mixed in smaller groups, therefore pen mean nested within room was used as a random factor. Adjusted group size was inserted as covariate to all models

(P = 0.046) higher post-weaning mortality rate (9.14 vs 4.98%) than pigs weaned old (d 37.5, SD = 0.3).

The interaction between age × regime, age × weight, and age × weight × regime did not significantly affect (P > 0.05) performance up to 7 weeks post-weaning (Table 5.4). However, significant interactions were observed between weight x regime for body weight at 7-weeks post-weaning (P = 0.044), for post-weaning ADG obtained between weaning and 7-weeks post-weaning (P = 0.046) and for ADG between 2- to 7-weeks post-weaning (P = 0.034). Pigs weaned light and fed the superior regime weighed 1.2 kg heavier at 7-weeks post-weaning than light pigs fed the control regime (37.6 kg, SD = 0.6 and 36.4 kg, SD = 0.6 respectively). Similarly, pigs weaned light and fed the superior regime showed higher ADG between weaning and 7-weeks post-weaning and between 2- and 7-weeks post-weaning (569 g/day, SD = 12 and 660 g/day, SD = 14 respectively) than light pigs fed the control regime (548 g/day, SD = 11 and 615 g/day, SD = 14 respectively). Pigs weaned heavy were 1.00 kg lighter at 7-weeks post-weaning, gained less between weaning and 7- weeks post-weaning, and between 2- and 7-weeks post-weaning when having access to the superior regime (41.3 kg, SD = 0.2; 581 g/day, SD = 12; and 665 g/day, SD = 15 respectively) than those fed the control regime (42.3 kg, SD = 0.2; 601 g/day, SD = 12; and 675 d/day, SD = 15 respectively).

Age and weight significantly (P < 0.01) affected post-weaning performance (Table 5.4). At weaning young pigs weighed 1.4 kg lighter than pigs weaned old (8.49 kg, SD = 0.17 and 9.91, SD = 0.19 respectively), this weight difference increased to -5.5 kg at 15-weeks post-weaning. Significant weight differences (P < 0.001) were also observed between pigs weaned light and H. At weaning, pigs weaned light (d = 34.6, SD = 0.3) were 3.2 kg lighter (7.60 kg, SD = 0.17 vs. 10.8, SD = 0.2) than pigs weaned heavy (d 34.6, SD = 3.0): this weight difference increased to -8.0 kg at 15 weeks post-weaning (93.0 kg, SD = 3.6 vs. 101, SD = 4). The main effect nursery feeding regime did not significantly (P > 0.05) influence post-weaning performance.

Performance to 20 and 60 kg. The interaction between weaning weight × nursery feeding regime significantly (P < 0.05) affected ADG from birth to 20 kg of weight (P = 0.046) and the number of days it took the pig to reach 20 kg (P = 0.027). Although no differences were seen for heavy pigs fed the superior or control nursery feeding regimes, light pigs fed the superior regime gained weight faster (348 g/day, SD = 5) and needed fewer days to reach 20 kg (53.9 d, SD = 0.7) when compared with light pigs fed the control regime (341 g/day, SD = 5 and 55.2 d, SD = 0.7 respectively). Also weaning age and weaning weight significantly (P < 0.05) affected ADG from birth to 20 kg (P = 0.002 and P < 0.001 respectively) and the number of days it took the pig to reach 20 kg (P = 0.001 and P < 0.001 respectively). Pigs weaned light had a lower ADG (344 g/day, SD = 5) and needed ~ 6 days longer (54.6 d, SD = 0.7) to reach 20 kg compared with pigs weaned heavy (385 g/day, SD = 5 and 48.2 d, SD = 0.7 respectively). Pigs weaned young on the other hand, gained weight faster (371 g/day, SD = 5) and needed 2 days fewer (50.3 d, SD = 0.7) to reach 20 kg compared with pigs weaned old (358 g/day, SD = 5 and 52.4 d, SD = 0.7 respectively). Similar results were seen for ADG between birth and 60 kg, with a significant (P < 0.05) effect found for weaning age and weaning weight for ADG (P = 0.020 and P < 0.001 respectively) and the number of days (P = 0.015 and P < 0.001 respectively); however, the interaction between weaning weight × nursery feeding regime was no longer significant (P > 0.05). Pigs weaned light gained less (566 g/day, SD = 7) and needed ~7 days longer to reach 60 kg (104 d, SD = 1) compared with pigs weaned heavy (604 g/day, SD = 7 and 97.3 d, SD = 1.4 respectively). On the other hand, pigs weaned young gained more (591 g/day, SD = 7) and needed 2.5 days less to reach 60 kg (99.5 d, SD = 1.4) than pigs weaned old (579 g/day, SD = 8 and 102 d, SD = 2 respectively).

Also the performance from weaning to 60 kg (i.e. ADG and days to reach 60 kg) was affected by weaning age (P = 0.055 and P = 0.007 respectively) and weaning weight (P = 0.007 and P < 0.001 respectively) but not by their interactions (P > 0.05). Pigs weaned light needed ~ 7 days more (72.3 d, SD = 1.7) and gained weight slower (734 g/day, SD = 16) between weaning and 60 kg compared with pigs weaned heavy (65.0 d, SD = 1.8 and 766 g/day, SD = 17 respectively). Pigs weaned young, however, tended to gain weight slower (739 g/day, SD = 17) and needed 3.6 days longer to reach 60 kg (70.4 g/day, SD = 1.7) compared with pigs weaned old (761 g/day, SD = 19 and 66.8 d, SD = 1.9 respectively). Although only numerical (P > 0.05) differences were seen between pigs weaned young and light and old and light with respect to ADG between weaning and 60 kg of weight (723 g/day, SD = 15 vs. 745 g/day, SD = 18), pigs weaned young and light required almost 4 days longer (P = 0.018) to reach 60 kg when compared with old and light pigs (74.1 d, SD = 1.6 vs. 70.4 d, SD = 1.8).

Feed intake and economic analysis. Total intake per pig (kg/pig), gain to feed ratio, total feed cost per pig, total feed cost per kg gain and MOF costs from weaning to 7-weeks post-weaning were not significantly (P > 0.05) affected by regime, age, and weight; the same (P > 0.05) was the case for the interactions weight × age, weight × regime, and age × regime. The total feed cost per pig was slightly higher for the pigs fed the superior compared those fed the control regime ($22.2/ pig, SD = 0.9 vs. $20.9/ pig, SD = 0.9). Pigs weaned young had a numerically lower MOF cost and total feed intake ($35.5, SD = 1.1 and 55.9 kg/ pig, SD = 2.0 respectively)

Table 5.5 Rank correlations between predictor variables for pigs weaned at a different weight and age excluding pigs that were weaned at an intermediate age (d 34). Within weaning age class: the bottom 50% were classified young and the upper 50% were classified old, pigs were split into 2 groups based on their weaning weight (light, bottom 50%; heavy, upper 50%). Morphometric measurements were taken within 12-24 h post-partum, pigs were weighed at birth (d 0) and at 2-3 days before weaning (d 31.7; SD = 2.6).[1,2]

Young Light

Predictor variable	BiW	TOTAL	Rel BiW	WW	ADG	WA	CRL	HL	AC	CC	BMI	PI	BiW: CC	HL: BiW
Birth weight (BiW), kg	-													
Total piglets born (TOTAL)	-0.395	-												
Relative Birth weight (Rel BiW)[3]	0.638	*ns*	-											
Weaning weight (WW), kg	*ns*	*ns*	*ns*	-										
Pre-weaning ADG (ADG), g/day	-0.208	*ns*	*ns*	**0.924**	-									
Weaning age (WA), day	0.203	*ns*	*ns*	*ns*	-0.364	-								
Crown to rump length (CRL), cm	**0.822**	-0.302	0.535	*ns*	-0.190	*ns*	-							
Snout to crown length (HL), cm	0.569	-0.267	0.323	*ns*	*ns*	*ns*	0.552	-						
Abdominal circumference (AC), cm	**0.841**	-0.351	0.507	*ns*	-0.163	*ns*	**0.766**	0.518	-					
Cranial circumference (CC), cm	**0.857**	-0.411	0.557	*ns*	-0.229	0.171	**0.771**	0.609	**0.780**	-				
Body mass index[4](BMI), kg/m^2	**0.711**	-0.285	0.488	0.143	0.144	0.251	0.201	0.325	0.528	0.546	-			
Ponderal index[5] (PI), kg/m^3	0.187	*ns*	0.150	*ns*	*ns*	0.189	-0.387	*ns*	*ns*	*ns*	**0.821**	-		
BiW: CC, kg/cm	**0.987**	-0.360	0.642	*ns*	-0.187	0.195	**0.803**	0.535	**0.822**	**0.774**	**0.721**	0.209	-	
HL: BiW, cm/kg	**-0.923**	0.329	-0.676	*ns*	0.179	-0.243	**-0.761**	-0.336	**-0.782**	**-0.765**	-0.699	-0.216	**-0.935**	-

Young Heavy

Predictor variable	BiW	TOTAL	Rel BiW	WW	ADG	WA	CRL	HL	AC	CC	BMI	PI	BiW: CC	HL: BiW
Birth weight (BiW), kg	-													
Total piglets born (TOTAL)	-0.447	-												
Relative Birth weight (Rel BiW)[3]	0.547	0.204	-											
Weaning weight (WW), kg	0.201	-0.190	*ns*	-										
Pre-weaning ADG (ADG), g/day	*ns*	*ns*	*ns*	**0.917**	-									
Weaning age (WA), day	*ns*	*ns*	*ns*	0.330	*ns*	-								
Crown to rump length (CRL), cm	**0.838**	-0.411	0.417	0.155	*ns*	*ns*	-							
Snout to crown length (HL), cm	0.529	-0.316	0.314	*ns*	*ns*	-0.166	0.534	-						
Abdominal circumference (AC), cm	**0.849**	0.346	0.461	*ns*	*ns*	*ns*	**0.748**	0.508	-					
Cranial circumference (CC), cm	**0.876**	-0.443	0.437	0.173	*ns*	*ns*	**0.792**	0.535	**0.780**	-				
Body mass index[4](BMI), kg/m^2	**0.724**	-0.244	0.494	0.160	*ns*	0.177	0.244	0.296	0.590	0.565	-			
Ponderal index[5] (PI), kg/m^3	0.162	*ns*	0.205	*ns*	*ns*	*ns*	-0.389	*ns*	*ns*	*ns*	**0.795**	-		
BiW: CC, kg/cm	**0.985**	-0.412	0.566	0.198	*ns*	*ns*	**0.818**	0.509	**0.835**	**0.788**	**0.733**	0.186	-	
HL: BiW, cm/kg	**-0.929**	0.350	-0.568	-0.249	*ns*	-0.228	**-0.791**	-0.313	**-0.804**	**-0.798**	**-0.703**	-0.178	**-0.936**	-

Old Light

Predictor variable	BiW	TOTAL	Rel BiW	WW	ADG	WA	CRL	HL	AC	CC	BMI	PI	BiW: CC	HL: BiW
Birth weight (BiW), kg	-													
Total piglets born (TOTAL)	*ns*	-												
Relative Birth weight (Rel BiW)[3]	**0.796**	*ns*	-											
Weaning weight (WW), kg	0.368	*ns*	0.359	-										
Pre-weaning ADG (ADG), g/day	*ns*	*ns*	0.191	**0.947**	-									
Weaning age (WA), day	*ns*	-0.476	*ns*	0.188	*ns*	-								
Crown to rump length (CRL), cm	**0.825**	*ns*	0.596	0.255	*ns*	*ns*	-							
Snout to crown length (HL), cm	0.598	*ns*	0.489	0.340	0.194	*ns*	0.567	-						
Abdominal circumference (AC), cm	**0.854**	*ns*	0.655	0.288	*ns*	*ns*	**0.742**	0.500	-					
Cranial circumference (CC), cm	**0.871**	*ns*	0.683	0.345	*ns*	*ns*	**0.755**	0.621	**0.722**	-				
Body mass index[4](BMI), kg/m^2	**0.703**	*ns*	0.635	0.386	0.203	*ns*	0.198	0.324	0.557	0.587	-			
Ponderal index[5] (PI), kg/m^3	*ns*	-0.192	0.227	0.190	*ns*	*ns*	-0.403	*ns*	*ns*	*ns*	**0.814**	-		
BiW: CC, kg/cm	**0.985**	*ns*	**0.792**	0.370	*ns*	*ns*	**0.811**	0.560	**0.853**	**0.782**	**0.703**	*ns*	-	
HL: BiW, cm/kg	**-0.920**	*ns*	**-0.756**	-0.365	-0.180	*ns*	**-0.782**	-0.409	**-0.806**	**-0.810**	-0.687	-0.185	**-0.929**	-

Old Heavy

Predictor variable	BiW	TOTAL	Rel BiW	WW	ADG	WA	CRL	HL	AC	CC	BMI	PI	BiW: CC	HL: BiW
Birth weight (BiW), kg	-													
Total piglets born (TOTAL)	-0.389	-												
Relative Birth weight (Rel BiW)[3]	0.562	*ns*	-											
Weaning weight (WW), kg	*ns*	-0.205	*ns*	-										
Pre-weaning ADG (ADG), g/day	*ns*	*ns*	-0.199	**0.928**	-									
Weaning age (WA), day	*ns*	-0.238	*ns*	0.635	0.386	-								
Crown to rump length (CRL), cm	**0.772**	*ns*	0.492	*ns*	*ns*	*ns*	-							
Snout to crown length (HL), cm	0.641	-0.298	0.340	*ns*	-0.190	*ns*	0.478	-						
Abdominal circumference (AC), cm	**0.855**	-0.351	0.554	*ns*	*ns*	*ns*	**0.708**	0.573	-					
Cranial circumference (CC), cm	**0.856**	-0.256	0.522	*ns*	*ns*	*ns*	0.668	0.580	**0.754**	-				
Body mass index[4](BMI), kg/m^2	0.652	-0.357	0.330	*ns*	*ns*	*ns*	*ns*	0.430	0.518	0.564	-			
Ponderal index[5] (PI), kg/m^3	*ns*	-0.214	*ns*	*ns*	*ns*	*ns*	-0.497	*ns*	*ns*	*ns*	**0.845**	-		
BiW: CC, kg/cm	**0.986**	-0.391	0.554	*ns*	*ns*	*ns*	**0.773**	0.620	**0.843**	**0.766**	0.637	*ns*	-	
HL: BiW, cm/kg	**-0.901**	0.260	-0.573	*ns*	*ns*	*ns*	**-0.762**	-0.356	**-0.797**	**-0.784**	-0.570	*ns*	**-0.908**	-

[1] Pearson correlation test was used to estimate correlations between continuous variables that were normally distributed. Variables with a high correlation ($r \geq 0.70$) are in bold. Morphometric measurements were taken within 12 h post-partum, pigs were weighed at birth (d 0) and 2-3 days before weaning (d 31.7; SD = 2.6).

[2] *ns* = not significant ($P > 0.05$)

[3] Relative birth weight = (Birth weight piglet/ mean birth weight birth litter)

[4] Body mass index = birth weight (kg)/[crown rump length (m)]^2

[5] Ponderal index = birth weight (kg)/[crown rump length (m)]^3

than pigs weaned old ($37.6, SD = 1.1 and 60.6 kg/pig, SD = 2.0 respectively). Also, pigs weaned light had a numerically lower MOF cost and total feed intake ($35.5, SD = 1.1 and 55.3 kg/ pig, SD = 2.0 respectively) compared with pigs weaned heavy ($38.1, SD = 1.1 and 61.2 kg/pig, SD = 2.0 respectively). Pigs weaned young and light had a numerically lower MOF cost compared with pigs weaned young and heavy ($33.6 vs. $38.2); old and heavy and old and light had a MOF cost of $37.9 (SD = 1.6) and $37.4 (SD = 1.6) respectively.

Predictor Variables for Post-weaning Performance. Correlations between variables for the different weaning age and weight groups (i.e. young and light, young and heavy, old and light, and old and heavy) excluding the 'intermediate' pigs are shown in Table 5.5. Overall and irrespective of treatment, high positive correlations ($r > 0.70$) were found between birth weight and various morphometric characteristics such as AC, CC, CRL, and BiW:CC. Birth weight was negatively correlated with HL:BiW. Correlations were also found between CRL and BiW:CC (positive), CRL and HL:BiW (negative), and positive correlations for the majority of groups between CRL and AC, and CRL and CC. Abdominal circumferences positively correlated with CC and BiW:CC, and negatively correlated with HL:BiW. As expected high positive correlations were found between BMI and PI and between BiW:CC and HL:BiW.

The univariate analysis assessing which predictor variables significantly affected ($P < 0.05$) post-weaning performance (ADG between weaning and 7-weeks post-weaning) is shown in Table 5.6. For pigs weaned young and light, birth weight, total born, CRL, AC, CC, BiW:CC, HL:BiW, weaning weight, and pre-weaning ADG were significant in the univariate analysis and were taken forward in the multivariate analysis. The final multivariate model for young and light pigs (Table 5.7) rejected birth weight as best predictor and showed that BiW:CC ($P < 0.001$) and weaning weight ($P < 0.001$) were positively associated with post-weaning ADG.

All predictor variables with the exception of PI, the total number of piglets born, and pre-weaning litter size significantly ($P > 0.05$) affected post-weaning performance of pigs weaned old and light. The best model fit for old and light pigs consisted of BiW:CC ($P = 0.044$), weaning age ($P = 0.043$), weaning weight ($P < 0.001$) and nursery feeding regime ($P = 0.027$); all positively associated with post-weaning ADG and with old and light pigs fed the superior regime having a greater growth. The final multivariate model for young and heavy compromised of BiW:CC ($P < 0.001$) and weaning weight ($P = 0.042$); and for pigs weaned old and heavy compromised of BMI ($P = 0.001$), BiW:CC ($P = 0.001$), and weaning weight ($P = 0.003$).

Table 5.6 Statistical significance (*P* - value) of the different predictor variables for post-weaning ADG (weaning and 7-weeks post-weaning) fitted in the univariate models for piglets weaned at a different ages and weights, excluding intermediate pigs (pigs weaned at d 34). At weaning the youngest 50% were classified 'young' and the oldest 50% 'old'; within age class pigs were split into 2 groups based on their weaning weight (light, bottom 50%; heavy, upper 50%). Morphometric measurements were taken within 12-24 h post-partum, pigs were weighed at birth (d 0), at 2-3 days before weaning (d 31.7; SD = 2.6), and at 7-weeks post-weaning.

Weaning age	Young		Old	
Weaning weight	Light	Heavy	Light	Heavy
Predictor variable				
Birth weight, kg	**<0.001**	**<0.001**	**0.001**	**<0.001**
Relative birth weight[1]	0.121	0.068	**0.011**	**0.001**
Total piglets born	**0.008**	**0.001**	0.099	**0.001**
Sex	0.814	0.960	0.271	0.521
Crown to rump length, cm	**<0.001**	**<0.001**	**0.002**	**0.004**
Snout to crown length, cm	0.319	**0.001**	**0.014**	**0.001**
Abdominal circumference, cm	**0.002**	**<0.001**	**0.001**	**<0.001**
Cranial circumference, cm	**0.026**	**<0.001**	**0.005**	**<0.001**
Body mass index[2], kg/m^2	0.100	**0.003**	**0.028**	**<0.001**
Ponderal index[3], kg/m^3	0.429	0.436	0.826	**<0.001**
Birth weight: Cranial circumference, kg/cm	**<0.001**	**<0.001**	**0.001**	**<0.001**
Snout to crown length: Birth weight, cm/kg	**<0.001**	**<0.001**	**0.001**	**<0.001**
Weaning weight, kg	**<0.001**	**0.009**	**<0.001**	**0.046**
Weaning age, day	0.243	0.425	**0.009**	**0.004**
Pre-weaning ADG, d/day	**0.010**	0.191	**<0.001**	0.816
Litter size pre-weaning[4]	0.921	0.999	0.270	0.516
Nursery regime[5]	0.051	0.139	**0.041**	0.680

[1] Relative birth weight = (Birth weight piglet/ mean birth weight birth litter)
[2] Body mass index = birth weight (kg)/[crown rump length (m)]2
[3] Ponderal index = birth weight (kg)/[crown rump length (m)]3
[4] Pre-weaning litter size = [(total time (h) piglets reside within litter/ pen)/24 h]/ total period in d
[5] At weaning pigs were randomly allocated to the different nursery regimes: either fed a high feed allowance regime in which pigs had a 65% greater allowance of the first and second stage feeds or the control regime.

5.5 Discussion

We investigated two management strategies that aim to address the challenge associated with pigs weaned lightweight: delaying weaning and specialist nutrition. Both strategies are based on the assumption that such pigs have different nutritional requirements than their 'normal' weight counterparts. Our hypothesis was that such pigs would perform better when weaned at a later age and/ or when fed more of the nursery feeding regime. Pigs weaned light that would benefit most from these strategies would be those born disproportional, i.e. piglets born with a dolphin-like forehead and those born long and thin (Douglas et al., 2016; Huting et al., 2018). These hypotheses were based on the findings that: 1) post-weaning growth check decreases with increasing weaning age (Colson et al., 2006; van der Meulen et al., 2010; Leliveld et al., 2013) and 2) lightweight pigs have an immature digestive system compared with their heavier counterparts (Cranwell et al., 1997; Pluske et al., 2003): thus increasing weaning age might be especially beneficial for them. We hypothesized that although piglets born disproportional have been suggested to have a reduced post-weaning performance (Douglas et al., 2016; Huting et al., 2018) and are known to be less efficient in nutrient utilisation (Wu et al., 2006), they may benefit when they are given a high quality nursery regime over a longer period of time. In addition, specialist feeding regimes (e.g. starter diets using readily digestible/ high quality nutrient sources with a high nutrient density) have been shown to be effective for lightweight pigs (Magowan et al., 2011a; Douglas et al., 2014a) and might have an additive or synergistic effect on the performance of these pigs which have been weaned either young or old.

Table 5.7 Final multivariate models (coefficient and SE) for different predictor variables for post-weaning ADG (weaning to 7-weeks post-weaning) for piglets from different weaning weights and weaning ages. At weaning, pigs were split into 2 groups based on their weaning age: the bottom 50% were classified 'young' and the upper 50% were classified 'old', within weaning age group pigs were classified 'light' (bottom 50%) or 'heavy' (upper 50%) on the basis of their weaning weight.[1]

Weaning age	Young		Old	
Weaning weight	Light	Heavy	Light	Heavy
Predictor variable				
Body mass index[2], kg/m^2	-	-	-	9.53 (2.86)
Birth weight: Cranial circumference, kg/cm	1758 (444)	3136 (535)	1354 (663)	2590 (735)
Weaning age, d	-	-	10.5 (5.13)	12.8 (4.2)
Weaning weight, kg	19.4 (4.7)	10.2 (5.0)	36.6 (6.7)	-
Pre-weaning ADG, g/day	-	-	-	-
Nursery feeding regime[3]	-	-	39.5 (17.6)	-

[1] Morphometric measurements were taken within 12-24 h post-partum, pigs were weighed at birth (d 0), at 2-3 days before weaning (d 31.7; SD = 2.6), and at 7-weeks post-weaning. Pigs weaned at an 'intermediate' age were excluded from the analysis.
[2] Body mass index = birth weight (kg)/[crown rump length (m)]^2
[3] The control regime was set at 0. At weaning pigs were randomly allocated to a different nursery regime: either fed a superior regime in which pigs had a 65% greater allowance of the first and second stage feeds or the control regime.

In the European Union, pigs are usually weaned at 4 weeks of age (European Commision, 2008). However, there are concerns about the health and welfare implications of this practice, especially in relation to the ban on the use of antibiotic growth promoters in 2006 (European Commision, 2003a) and the restrictions on the prophylactic use of copper and zinc (European Commision, 2003b; European Commision, 2016). Weaning is accompanied by a drop in intake and a reduced digestive and absorptive capacity, negatively affecting gut health (Pluske et al., 1997; Lallès et al., 2007). Older weaned pigs have a more mature digestive system (Cranwell et al., 1997; Pluske et al., 2003), with delayed weaning positively affecting the mucosal permeability and the motility of the gut (Moeser et al., 2007), decreasing the proliferation of pathogenic bacteria (Wellock et al., 2007; Leliveld et al., 2013) and reducing mortality rate (Leliveld et al., 2013). These, together with the higher post-weaning feed intake (van der Meulen et al., 2010), suggest that pigs weaned older recover more quickly from the post-weaning diet transition than pigs weaned young. This suggests that increasing weaning age might be the way forward under current EU regulations for reducing the potential negative effects the ban on antibiotic growth promotors may have on performance and welfare.

Previous large-scale investigations, such as during the "AGEWEAN" project (Edge et al., 2008) have suggested that delaying weaning to 6 weeks of age has beneficial consequences on the number of pigs needing veterinary treatment or dying post-weaning. This was also the finding of our study, as post-weaning mortality was almost double for pigs weaned earlier (young pigs). However, when the overall performance of the pigs in the 'AGEWEAN' study was evaluated, weaning pigs at 4 weeks of age was still considered to be more efficient (Edge et al., 2008), although the authors emphasized that not all pigs were followed until slaughter. Colson et al. (2006) and Leliveld et al. (2013) similarly reported that, although the growth depression was larger and lasted longer for early compared with late weaned pigs (3- vs. 4-weeks of age), this only influenced performance during the intermediate post-weaning period and had no long-term consequences (to 10-weeks of age). Despite that our pigs were weaned relatively old, our study suggests that pigs weaned young gained less between weaning and 60 kg live weight and needed almost 4 days extra from weaning to 60 kg than pigs weaned old. The latter may contribute to increased feed costs, with young pigs being introduced to the expensive grower and/or finisher diets for a longer period of time than pigs weaned old. Although not supported by the MOS results of this study. Although, weaning light pigs later may be attractive way to improve their post-weaning performance, to evaluate the cost effectiveness of such strategy the additional sow costs (e.g. feeding, housing) needs to be taken into consideration.

In this study we were particularly interested in whether increasing weaning age for light pigs would be beneficial, as the aforementioned concerns may be exacerbated in lightweight pigs. Split weaning, i.e. weaning the heaviest piglets of the litter 3-7 days before the rest of the litter, is thought to reduce the weaning-to-oestrus interval (Soede and Kemp, 2015) and to increase pre-weaning performance for the remaining piglets, compared with piglets that were weaned at the same calendar age but not split weaned (Pluske and Williams, 1996a; Vesseur et al., 1997). Literature is inconsistent with respect to whether pigs that remained on the sow longer after split-weaning could retain the body weight advantages at weaning in later life. Some suggest that the body weight advantage does not persist in the long term (split weaning at d 21 vs.

weaning at d 28) (Pluske and Williams, 1996a; Vesseur et al., 1997), while under tropical conditions it was reported that light pigs that remained on the sow until d 53 after split weaning (at d 28) were heavier at 15-weeks of age compared with light pigs that were either weaned early (d 28) or as a whole litter at the same age (d 53) (Abraham et al., 2004). Although split weaning was not practiced in this study and all pigs were weaned at the same day irrespective of the date of birth, the results presented demonstrate that light pigs benefitted from later weaning (old), needing approximately 4 days less to reach 60 kg compared with light pigs that were weaned 6 days earlier (young). Leliveld et al. (2013) also found that an increase of 1 kg in weaning weight resulted in a 2.3 or 1.8 kg weight advantage at 10-weeks of age for pigs weaned at 3 or 5 weeks respectively, thus emphasizing that weaning age is more important for pigs weaned light. Pigs end up light at weaning as a result of: 1) being born light and/or disproportional, 2) insufficient colostrum intake, 3) direct and indirect competition for milk intake, or 4) due to illness (Declerck et al., 2016a; Douglas et al., 2016; Huting et al., 2017, 2018). Increasing weaning age for these pigs might stimulate gut maturity, with components in the milk altering the intestinal microflora important for the development of the gastrointestinal tract and the immune system, as shown in human infants (Fanaro et al., 2003; Schack-Nielsen and Michaelsen, 2007). In addition, creep feed intake increases with increasing weaning age (Defra, 2007), positively influencing post-weaning feed intake (Muns and Magowan, 2018).

Nutritionists have been suggesting specialist feeding regimes for light pigs as another way to compensate for the immature digestive system and lower feed intake of light pigs, and maximize post-weaning performance (Douglas et al., 2014a). These range from enhanced diet composition, improving the digestibility and palatability of the nursery feeding regimes (Beaulieu et al., 2010b; Douglas et al., 2014a), or feeding a greater allowance (kg/ pig basis) of the nursery regime (Magowan et al., 2011a; Douglas et al., 2014a; Muns and Magowan, 2018). This may increase voluntary feed intake, but the use of readily digestible nutrients may reduce the amount of substrate passing the large intestine, thus improving intestinal health (Wellock et al., 2009). In this experiment, we opted for the latter strategy because of its practicality, which was achieved by feeding lightweight pigs for a longer period of time on the nursery feeding regimes. The experimental outcomes suggest that pigs weaned light were able to improve post-weaning performance when having access to the superior regime. Mahan et al. (1998) also found that feeding the first phase regime for 2 weeks instead of 1 week reduced the number of days it took light pigs to reach slaughter weight; they reported however, that weaning weight still had a greater effect on post-weaning performance than feed allowance (Mahan et al., 1998). Likewise in this experiment, the increased amount of kg/pig of diet 1 and 2 was not enough to maximize the growth of light pigs. What is interesting is that the performance of the heavy pigs was not affected by the increased amount of the nursery feeding regime consumed, questioning the need for this strategy for this class of pigs. We expected that the higher feed allowance would also improve the performance of pigs weaned heavy, but that it would not be economically viable.

It should be emphasized that the advantages of the superior regime for the light pigs soon after weaning were not sustained in the long term, in agreement with Magowan et al. (2011b). When their performance was considered to 60 kg, there was no longer a nursery feeding regime effect or a weaning weight × regime interaction. Also others (Magowan et al., 2011a) who fed 100% more of the first stage nursery feeds showed that the body weight advantage during the immediate post-weaning period was not sustained in the long term. This questions the successfulness of the higher allowance nursery feeding regime for lightweight pigs.

We have shown previously that some morphometric traits of the lightweight piglets are good predictors of post-weaning performance (Douglas et al., 2016; Huting et al., 2018). Also in this study, it became clear that not all lightweight pigs are alike and some are able to perform better than the others. Irrespective of weaning age, pigs weaned light most likely to remain light were characterized by a disproportionate head circumference in relation to size (low BiW:CC) and a lower weaning weight. The larger head in relation of size may characterize piglets that suffered from IUGR and remain stunted throughout life (Amdi et al., 2013). On the other hand, post-weaning performance of pigs weaned old and light was positively associated with weaning age and nursery regime. The greater weaning age variation for pigs weaned old and light when compared with young and light might explain why weaning age affected the performance of old and light pigs only. What was interesting was that the nursery feeding regime influenced old and light pigs only. Although, light pigs are thought to have a less developed digestive system (Cranwell et al., 1997; Pluske et al., 2003), creep feed intake increases with weaning age (Defra, 2007). The latter may have prepared the digestive tract of old and light pigs for weaning resulting a smaller growth check. The feed allowance for young and light pigs might not have been sufficient to support their performance.

5.6 Conclusion

We have found that both increasing weaning age and feeding higher quantities of the first diets in the post-weaning nursery feeding regime (on a kg/pig basis) are beneficial for pigs weaned light. Although the latter strategy could be easily implemented in pig units that separate pigs on the basis of weaning weight, the benefits were not sustained in the longer term. While more research is needed, it is recommended that delayed weaning may yield longer term improved post-weaned performance for pigs weaned light.

Chapter 6.

General discussion

The aim of this thesis was to develop management strategies that will reduce weight variability within the pig herd by enabling piglets born and or weaned light to increase their body weight gain without penalizing the performance of their heavy counterparts. In addition, this thesis aimed to provide understanding on whether all light piglets need to be treated the same or whether a tailor made solution for different classes of light piglets is necessary. This is important since all light piglets are thought to contribute to severe economic losses, due to their higher mortality rate, slower growth rate, and poorer gain to feed ratio.

This thesis has emphasized that not all light piglets are alike. In fact, some light piglets, identified by their morphometric characteristics at birth, are able to decrease their deficit in body weight pre- and post-weaning without any interventions. This thesis has also demonstrated ways to improve the performance of piglets born and or weaned light, without penalizing the performance of heavy piglets. Some of these strategies were effective, whereas others were not or their beneficial effects did not persist in the long term. In addition, some of these strategies penalized the performance of heavy piglets, thus should not be applied to all animals emphasizing that light piglets have special needs. Initially, we investigated the effects of cross-fostering in order to create litter uniformity on the long-term performance of piglets born light and heavy (Chapter 2). One of the supplementary aims of this chapter was to access whether the availability of creep feed enabled piglets, irrespectively of birth weight, to compensate for the lack of resources when reared under suboptimal conditions (i.e. increased competition). As reducing competition with heavy piglet benefitted light piglets pre- and post-weaning performance, the next step was to evaluate which foster sow parity (primiparous, second and mid parity sows) was able to maximize light piglets performance when reared in uniform litters (Chapter 3). Subsequently, intervention strategies during the immediate post-weaning period were assessed. The effectiveness of a nutrient enriched regime (higher in amino acid: energy ratio) to enable light piglets to compensate for the low post-weaning feed intake was tested (Chapter 4). In the last chapter the effect of weaning age and an increased allowance of the first stages of the nursery feeding regime on the performance of piglets weaned light were investigated (Chapter 5). The consequences of all these strategies were also evaluated for heavy piglets as these strategies may be beneficial for light piglets, but may penalise heavy piglet performance. Ultimately the findings of this thesis have provided some management guidelines in order to minimize body weight variation within batch and emphasised the need for a tailor made solution for different classes of light piglets.

6.1 Can lightweight piglets reduce their growth deficit?

Most literature identifying risk factors for high mortality rate and poor prenatal performance has identified birth weight as one of the key factors (Paredes et al., 2012; Douglas et al., 2013). Results of this thesis confirm previous findings; light piglets (< 1.25 kg) had a 9% higher pre-weaning mortality rate, had a higher likelihood to remain light at finisher, and were 5 kg lighter the day before slaughter while needing approximately 5 days longer to reach this weight (90-100 kg) than piglets born heavy (1.5 to 2.0 kg) (Chapter 2 to 4). The poorer postnatal performance might be attributed to differences in stomach capacity (Michiels et al., 2013; Huygelen et al., 2015; Lynegaard et al., 2018), in muscle fibre composition (Gondret et al., 2006; Wang et al., 2008), in energy (Getty et al., 2015) and carbohydrate metabolism (Gajewski et al., 2018) and alterations in the gastrointestinal tract (Michiels et al., 2013; Li et al., 2018), which may prevent light piglets from showing compensatory growth. Furthermore, weaning weight has been identified as key factor influencing the days to reach market weight (de Grau et al., 2005; He et al., 2016) and the data from this thesis confirm that piglets weaned light had a poorer post-weaning performance, weighing 5 kg less at the end of the nursery period than piglets weaned heavier. However, our findings also suggest that only 48% of the piglets weaned light were born light, whereas the rest were born heavier. Only a weak positive correlation ($r < 0.40$) was found between birth and weaning weight, whereas a high positive correlation was found between ADG and weaning weight ($r > 0.95$). There are many factors that may contribute to poor pre-weaning performance such as colostrum intake, milking ability of the sow, litter composition, teat position, litter size, and sickness (Devillers et al., 2011; Huting et al., 2017), things that a pig producer can control only to a certain extent. Although piglets born heavy are considered quite robust (Baxter et al., 2013), many of the aforementioned factors not only influence the performance of piglets born light, but may also impair the performance of piglets born heavier (Chapter 2 to 3). The results in this thesis indicate that although piglets born heavy but weaned light had a poorer pre-weaning performance when compared with piglets born and weaned light, they performed better during the post-weaning period (Chapter 4). This finding indicates that once feed was available *ad libitum* the former were able to decrease their growth deficit (Douglas et al., 2014a) compared with the latter but they were unable to catch up growth with piglets born heavy and weaned heavier, which may in turn suggest that the limited milk intake during lactation sets animal appetite during later life (Hales and Barker, 2001).

This thesis has also made a valuable step towards a better understanding to what allows some piglets to compensate for their growth deficit at birth or weaning. The reason why some light piglets are able to compensate for their growth deficit whereas others remain stunted has been uncertain (Douglas et al., 2016). In Chapter 4, a first attempt was made to assess piglet traits that predispose light piglets to a poor pre- and post-weaning performance under commercial farm conditions. It is clear that specific morphometric characteristics were better indicators than birth weight both pre- and post-weaning, which suggests that piglet ability to catch up may be dependent on piglet intrauterine environment (Douglas et al., 2016; Hansen et al., 2018). In particular, piglets born with a greater head in relation to birth weight and with a long and thin body (low PI and BMI) appear to be in a disadvantage. For instance, piglets with a low BMI and/ or PI may have a higher surface area: volume ratio (Amdi et al., 2013) or may have suffered from intrauterine malnutrition compared with piglets with a similar body weight but with a higher BMI and/ or PI. In addition, the larger head size in relation to birth weight may indicate towards a dolphin-like forehead commonly seen is IUGR piglets (Hales et al., 2013). This finding was later confirmed at a large farrow-to-finish commercial farm (Chapter 5). Our results clearly show that focussing on birth weight only for mortality but also post-weaning performance (Huting et al., 2018) overestimates the prevalence of growth retardation (Wollmann, 1998); intrauterine growth retardation (IUGR) piglets will be small for gestational age (SGA), but not all SGA piglets are IUGR. This result is especially important considering that ~25% of the piglets is considered light (< 1.25 kg; Douglas et al., 2013), whereas around 10-15% of the live born piglets may be born IUGR (Chevaux et al., 2010; Hansen et al., 2018; Matheson et al., 2018), though not present in all litters (30% of the litters did not show signs of IUGR; Matheson et al., 2018) and varied between sow parity (Chevaux et al., 2010; Matheson et al., 2018). For instance, more piglets from primiparous sows showed signs of IUGR (Matheson et al., 2018) and also the prevalence of IUGR in multiparous sows (> parity 5) went up to 25% (Chevaux et al., 2010). In addition, for those that do survive piglet's morphology at birth, may also influence the effectiveness of the management strategies commonly applied to help light piglets catch up growth. Surprisingly, many studies looking at the effectiveness of interventions, for instance investigating the effects of post-weaning feeding strategies on performance of piglets with various weaning weights, select piglets on the basis of weaning weight only. This may also be the case for pig producers who size their pigs at weaning on the basis of weaning weight and may thus influence the (cost) effectiveness of applied strategies. This especially important considering that the prenatal environment of growth restricted piglets has resulted in piglets that could survive under resource limiting conditions, but may not able to benefit from a nutrient rich environment (Gluckman et al., 2005). It should be noted however, that the differences in head morphology change over time, IUGR piglets will "lose" their typical dolphin shaped head characteristics at 2 weeks of age (Amdi et al., 2014) thus the differentiation between IUGR and SGA should be done as early post-partum as possible.

Although, out of the scope of this thesis, it remains uncertain whether the piglets that remained stunted would be able to improve their performance when rearing conditions would be optimal (e.g. colostrum intake, limited competition, specialized nutrition) or whether their growth potential is the limiting factor (Douglas et al., 2016; Amdi et al., 2017; Hansen et al., 2018). The allocation of the piglets to the different experimental groups in this thesis was mostly based on body weight (i.e. birth or weaning weight) with shape at birth not taken into consideration. The latter, may also have had an effect on the results obtained in this thesis when evaluating the effectiveness of the different management strategies. On the other hand, it is believed that around 10-15% of the live born piglets may be born IUGR (Chevaux et al., 2010; Hansen et al.,2018; Matheson et al., 2018) and given that the majority of the studies as presented in this thesis were performed on a small research farm, this left us with only ~20-30 piglets per farrowing batch that may have been born IUGR. Furthermore, the determination of clear cut-off points for BMI and PI for piglets that are at risk for a poor pre- and/or post-weaning performance are lacking and warrant further research at large scale pig units.

6.2 Improving pre-weaning performance of lightweight piglets

Piglet milk intake is one of the limiting factors pre-weaning, which may be influenced by littermate weight, teat position, litter size and sow parity. Reducing litter competition has been shown beneficial for light piglets increasing weaning weight by 6% with the weight advantage being maintained up to finisher (Chapter 2). Creating litter uniformity as commonly applied in commercial practice, however, may not restrict itself to piglets born light but also piglets born heavy. Heavyweight piglets are suggested to compensate for any adverse effects by consuming creep feed. However, what is good for light piglets might not be good for heavy piglets. In fact, Chapter 2 illustrated that heavy piglets were penalized when reared with similar sized piglets, increasing the competition for teat access and milk intake (King et al., 1997; Baxter et al., 2013; Hales et al., 2013). Although, they tried to compensate for the inadequate milk intake when reared with similar sized piglets by consuming high amounts of creep feed, this seemed insufficient to improve their pre- and post-weaning performance. Creep feed was offered from d 10 onwards while heavy piglet performance was already penalized before this period, as indicated by the higher removal rate of heavy piglets. Thus, supplying them with an alternative nutrient source (e.g. creep feed or milk replacer) before d 10 would have possibly enabled them to improve their pre-weaning performance. On the other hand, solid feed intake up to 3 weeks post-partum was low and piglets showed more exploratory behaviour if anything else. Therefore, supplying them with a milk replacer would have been the preferred strategy for heavy piglets to overcome the milk deficit.

Although, taken the practical limitations of the research farm (i.e. the number of sows, the number of piglets) into consideration, it would have been good to also test the effect of certain management strategies (for instance those described in Chapter 2) on the performance medium piglets (1.25 – 1.50 kg). Mixing light piglets with medium piglets might not be as detrimental for their performance than for instance mixing light piglets with heavy piglets as done in this thesis. In addition, creating litter uniformity with medium piglets only might be less unfavorable than as what has been observed for heavy piglets. The latter, warrants further research on a large scale pig unit.

Irrespective of birth weight, primiparous sow reared litters performed worse pre- and post-weaning compared with piglets reared by second and mid parity sows weighing 500 g less at weaning which increased to 1.5 kg at 10 weeks of age. Although Craig et al. (2017) attributed the lower performance of primiparous reared piglets mainly to their lower birth weight as compared to that of multiparous reared piglets, performance differences were present in the present thesis even after standardizing litters for litter size and birth weight. This difference in performance may be attributed to differences in milk yield (Bierhals et al., 2012; Miller et al., 2012; Carney-Hinkle et al., 2013), and/or differences in milk composition between primiparous and multiparous sows (Craig et al., 2018). Piglets reared by mid parity sows performed best pre- and post-weaning consuming high amounts of creep feed and being weaned heavy. Second parity sows reared piglets on the other hand, were weaned heavy but their limited creep feed consumption during lactation penalised their post-weaning performance. This was surprising as second parity sows were suggested to have a similar milk yield as mid parity sows (Beyer et al., 2007; Hansen et al., 2012; Ngo et al., 2012). Teat quality has been suggested to be one of the factors that might have limited mid parity sow reared piglets performance as indicated by their high creep feed intake. On the other hand, the lactation curve, i.e. when milk yield reaches a plateau, which in sheep seems to be dependent on parity (Ruiz et al., 2000; León et al., 2012) may have played a role though still warrants future research. In addition, most studies assessing milk yield, do not take birth weight into consideration considering only gain between birth and weaning (Hansen et al., 2012), whereas birth weight may determine how well a piglet is able to massage a teat and thus affect subsequent milk let down (King et al., 1997; Drake et al., 2008) and milk yield. Nonetheless, these results suggest that it might be better to rear light piglets by multiparous sows than primiparous sows. On the other hand, caution should be taken when interpreting these results as piglets reared by mid parity sows mostly benefited post-weaning from their high creep feed intakes and weaning weight advantage while light piglets hardly consumed creep feed irrespective of foster parity. This suggests that the positive effect of mid parity sows on pre- and post-weaning performance may have mostly originated from the improved performance of heavy piglets as supported by the > 2.0 kg numerical differences at 10 weeks of age between heavy piglets reared by mid parity sows versus heavy piglets reared by gilt or second parity sows and not light piglets (difference was only 600 g).

The litter sizes in UK (average 12.5 born alive/litter) are quite low compared with the EU average (average 13.9 born alive/ litter; AHDB Pork (2016)), which may have influenced the outcomes of the effectiveness of the pre-weaning management strategies as tested in this thesis. However, it is expected that the negative effects seen on the performance of light and heavy piglets when reared under suboptimal conditions (i.e. litter composition, sow parity) would be aggravated in larger litters due to the increased competition for the already limited resources. In addition, the piglet management practices applied such as locking piglets in the creep area during the first 2 days and providing milk replacer during the first 4 days of life may have influenced the mortality rate. Although mortality rate of light piglets was not affected by litter composition in this thesis, it is expected that under commercial conditions where labour is scarce/ expensive and in the very highly prolific sows light piglets reared in mixed litter would have a higher risk to die than light piglets reared in uniform litters. Birth weight remained to play a greater role on post-weaning performance than the management strategies applied and whether the beneficial effects of certain pre-weaning strategies persist on the long term, depends on how pigs are managed afterwards. For instance, mixing piglets has severe consequences on piglet well-being as it increases fighting, reduces post-weaning feed intake (Callaway et al., 2006; Hötzel et al., 2011), but may also result in a higher abundance of pathogenic bacteria in the gut (Callaway et al., 2006), which may in turn increase the risk of digestive disorders. In most of the Chapters in this thesis (Chapter 2 and 3) piglets remained together with their litter mates as the pen sizes at the University farm could be adjusted to accommodate smaller groups of piglets (≤ 12 piglets/pen). However, in practice it is almost inevitable to prevent mixing of animals due to the greater pen sizes (> 20 piglets/pen), and may have consequences for the successfulness of the pre-weaning management as the beneficial effects at weaning may not be retained post-weaning.

6.2.1 *Individual creep feed consumption*

The methods used for the identification of consumers using an inert dye are only able to categorise piglets into certain consumer classes but do not indicate how much a piglet has eaten. Furthermore, the amount of dye that recovers in the faeces is dependent on several factors such as the amount eaten, piglet consistency of eating creep feed, the gastrointestinal transit time and piglets milk intake as milk may mask the dye (Barnett et al., 1989; Kuller et al., 2007c). Although, feed intake (intake/litter) and feeding behaviour were positively correlated ($r = 0.69$) also the identification of behaviours towards the feed hopper have their limitations. For instance, not every piglet that shows interest in the hopper will also eat something and analysing all these data is very labour intensive. Designing a feeding station to accurately estimate individual creep feed intake might be useful, however there are certain behaviours that stimulate creep feed intake. For instance, exploration behaviour (Kuller et al., 2010; Adeleye et al., 2014; van den Brand et al., 2014) and the interaction between piglets (Wattanakul et al., 2005), i.e. the individual that starts eating creep feed may motivate other piglets to consume creep feed (Oostindjer et al., 2014). However, a feeding station that only allows one piglet to eat at a time might limit piglets to fully express these behaviours negatively influencing the number of eaters. Furthermore, the creep feed should be supplied fresh and to keep piglets interested feeding multiple times a day of small quantities of feed is preferable (AHDB Pork, 2017b).

In this thesis we therefore further developed the use of inert dye in the creep feed. The use of the colour reader enabled us to objectively measure the colour and the colour intensity (e.g. a*) of the faecal samples at different time points. Although this methodology needs further development, it was interesting to observe that also piglet's faeces from non-creep fed litters became greener with age, suggesting that a green dye such as chromic oxide might not be the best dye to use. Therefore, it would be advisable to use a dye with a colour spectrum that deviates from the normal faecal colour in future studies.

The total amount of consumers (~ 50%) in this thesis is quite low compared with other studies (> 70%). This difference may be due to the inclusion of light piglets here, as opposed to previous studies where average piglets (birth weight 1.4 kg) were studied only (Sulabo et al., 2010; Middelkoop et al., 2018). Moreover, the methodology used for the identification of consumers is different as in some studies eaters were classified by scan sampling (Middelkoop et al., 2018), which may overestimate the number of consumers as not each piglet placing its snout in the feeder will consume feed. Additional factors that may have played a role are differences in the parity of used sow's and litter size (Klindt, 2003).

Solid feed intake during lactation is suggested to prepare the piglet for weaning, with piglets eating high amounts of creep feed starting to consume sooner and having a greater post-weaning gain than non-consumers (Bruininx et al., 2002; Kuller et al., 2007a). Creep feed intake was the highest during the last week before weaning (> d 21), around the time that milk yield plateaus (Hansen et al., 2012) but piglet nutritional requirements increases. Since creep feed intake varies amongst piglets and amongst litters and is generally eaten in very low quantities (van der Meulen et al., 2010), creep feed provision is unable to improve weaning weight at 4 weeks of age, as confirmed by the results of Chapter 2. However, it should be noted that weaning age plays a detrimental role in the effectiveness of creep feed to improve weaning weight (van der Meulen et al., 2010). For instance, creep feed provision for piglets weaned later than 4 weeks of age, i.e. 7 weeks of age (creep feed intake ~600 g/d the day before weaning), was able to increase weaning weight whereas no differences was seen for piglets weaned at 4 weeks of age (creep feed intake 100 g/d the day before weaning; van der Meulen et al., 2010). In addition, it should not be forgotten that creep feed is an alternative nutrient source and will not replace sow milk during lactation. In fact milk is known to contain important growth factors that are essential for the development of the digestive tract and immune system (Fanaro et al., 2003; Schack-Nielsen and Michaelsen, 2007). Nevertheless, this thesis has clarified that although high consumers were those gaining less during the initial 3 weeks post-partum weighing 700 g less at d 19 compared with non-consumers, they performed better during the post-weaning period than non-consumers (Chapter 2 and 3). Factors that appear to influence individual creep feed intake where teat position, litter composition, sow parity, and birth weight. For instance, piglets suckling the posterior teat pair classes (i.e. teat pair ≥ 6) had the lowest likelihood of becoming a non-consumer and the highest likelihood of becoming a high consumer compared with piglets suckling the anterior and middle teat pair classes (i.e. teat pair 1-2 and 3-5, respectively). In addition, piglets reared by primiparous and mid parity sows had a higher likelihood to be considered consumer than piglets reared by second parity sows.

Previous studies evaluating the effect of birth weight on pre-weaning eating behaviour were often conflicting (Pajor et al., 1991; Bruininx et al., 2004; Sulabo et al., 2007). Both Chapter 2 and 3 have illustrated that light piglets hardly consume creep feed (< 100 g/piglet) compared with heavy piglets (>200 g/piglet). Although differences in sow milk yield represented by the different sow parities stimulated heavy piglets to compensate by consuming high amount of creep feed represented by the different consumer classes, no differences were seen for light piglets. This might have two explanations: 1) sow milk is sufficient to meet light piglet requirements (Pajor et al., 1991; Foxcroft et al., 2006) or 2) their digestive system is too immature compared with heavy piglets (Michiels et al., 2013). However, Huygelen et al. (2015) recently suggested that although light piglets have a lower absolute stomach weight, but a greater relative stomach weight compared with heavy piglets, no differences were observed with respect to small intestines motility, morphology and the activity of the brush border enzymes throughout lactation (Huygelen et al., 2015). This may suggest that the limited amount of milk consumed by light piglets might have been enough to meet their requirements. To evaluate whether light piglets can ingest more milk when given the change or whether their requirements are just low, a study should be performed in which light piglets are kept in varying litter sizes (e.g. 8 vs. 12 piglets).

6.3 Improving post-weaning performance of lightweight piglets

Weaning is accompanied with various stressors including dietary stressors. Piglets go from a liquid feed available every 45-60 minutes to a predominantly cereal based diet which is available *ad libitum*, whilst their digestive system is not mature enough to handle this abrupt dietary change. Weaned piglets have a relatively high gastric pH compared with sow-reared piglets (Efird et al., 1982), which may result from their lower hydrochloric acid secretion capacity along with a reduced lactic acid production from lactose (Cranwel et al., 1976). On the other hand, the presence of some protein rich feedstuffs in the weaner diets may have a buffering effect increasing stomach pH (Cranwel et al., 1976; Efird et al., 1982). An acid stomach pH (pH 2.5 to 3.0) is necessary to maintain the stomach barrier function against pathogenic bacteria, but also to enable the conversion of pepsinogen into pepsin, which is crucial for breaking down proteins into smaller peptides. The high stomach pH together with the rapid gastric emptying rate of newly weaned piglets (Boudry et al., 2004) decreases gastric proteolysis and nutrient digestibility and may increase the passage of pathogens into the small intestine. Furthermore, villus hypertrophy and inflammation of the intestinal wall, as a result of post-weaning anorexia, and various stressors (i.e. social, environmental, and dietary stressors) that may influence gut permeability (Wijtten et al., 2011), reduce the absorption and digestive capacity of the small intestine increasing the proportion of undigested substrates entering the large intestine (Heo et al., 2013). Collectively the aforementioned factors reduce growth performance while increasing disease susceptibility and scouring.

Villous length and crypt depth seem to linearly increase with dry matter intake (Pluske et al., 1996), thus increasing feed intake during the immediate post-weaning period is detrimental. Another key factor for a good post-weaning regime is reducing the amount of undigested substrate, in particularly undigested proteins, entering the large intestine that otherwise would encourage the growth of proteolytic bacteria. Especially, since after a period of fasting piglets will get extremely hungry and start eating relatively high amounts of feed while their digestive system is still damaged and unable to digest and absorb all the ingested nutrients (Heo et al., 2013).

6.3.1 *Specialised feeding*

Especially light piglet are thought to have a less developed digestive system at weaning (Cranwell et al., 1997; Pluske et al., 2003; Michiels et al., 2013). One of the characteristics that impair light piglets post-weaning performance is their lower feed intake (Magowan et al., 2011a) which may be due to their lower stomach size (Huygelen et al., 2015) or their low creep feed consumption (Chapter 2 to 3) contributing to their inability to get accustomed to the abrupt dietary change at weaning. A low feed intake during the immediate post-weaning period (1^{st} week post-weaning), which negatively influences gut morphology (e.g. decreased villi height and increased crypt depth) contributes to intestinal inflammation (Pluske et al., 1996) and has been associated with an increased risk for succumbing to post-weaning digestive disorders (Madec et al., 1998). Research evaluating post-weaning starter regimes specifically designed for light piglets suggests that feeding nutrient dense diets with highly digestible and very palatable feed ingredients (Beaulieu et al., 2010b; Douglas et al., 2014a) is the way forward, promoting feed consumption soon after weaning and simultaneously preventing indigestible substrates from entering the distal part of the digestive tract. Although, it was hypothesised that the nutrient enriched regime in Chapter 4 should enable light piglets to compensate for the insufficient feed intake the dietary regime was unable to improve the performance of piglets born or weaned light. Multiple explanations have been put forward among which that light piglets do not have a higher amino acid requirements (Tokach, 2004) or that the piglets did not have access to enough energy to utilise the additional amino acids. Another explanation could be the lack of focus on specific amino acids. It has been shown that light pigs have a lower ghrelin expression in the gastric cells (Willemen et al., 2013) and have lower concentrations of serotonin, the precursor of tryptophan (Willemen et al., 2014). Therefore an increased supplementation of tryptophan may stimulate appetite, preserve health during inflammation (Le Floc'h et al., 2011; 2012), and support the serotonergic system essential for feeding behaviour and the synthesis of insulin-like growth factors (Willemen et al., 2014). Also glutamine and arginine are believed to enhance postnatal growth via the secretion of anabolic hormones (Roth, 2007) and improve survivability (Li et al., 2017) by serving as an important fuel for immune cells (Roth, 2007; Wu et al., 2011). An increased threonine supply which is essential for maintaining intestinal integrity in newly weaned pigs (Le Floc'h et al., 2012) might also favour light piglets.

It should be noted however that the diets studied in Chapter 4 and 5, have a relatively high crude protein content of over 20% (AHDB Pork, 2010), which might become problematic due to the further reduction on using in feed antibiotics (European Commision, 2003a), further restrictions in the use of zinc oxide and the restrictions with respect to pharmaceutical levels of copper in 2019 (European Commision, 2003b; European Commision, 2016). The prophylactic use of antibiotics and the pharmaceutical levels of zinc oxide and copper in the diet are all known for their antibacterial properties, their role in gut structure and function reducing the risk for gastrointestinal infections, increasing feed intake and improving piglet post-weaning performance (Sun and Kim, 2017). It is well known that the lack of these in-feed antibiotics may become problematic when supplying high amounts of crude protein (Wellock et al., 2006; Wellock et al., 2009). High dietary crude protein levels are suggested to increase the risk of post-weaning diarrhoea, due to undigested protein entering the large intestine resulting in protein fermentation. The higher piglet removal rate of piglets fed the nutrient enriched regime (i.e. higher in essential amino acids) compared with piglets fed the standard regime, might be an indication that the crude protein concentration in relation to the NE content used might have been too high, resulting in the surplus of crude protein being fermented.

Feeding the high quality diets for a longer period of time, as studied in Chapter 5, was beneficial for piglets weaned light up to 7 weeks post-weaning irrespective of their weaning age. Differences in digestive capacity between light and heavy piglets at weaning (Cranwell et al., 1997; Pluske et al., 2003; Michiels et al., 2013) may suggest that light piglets would benefit from a readily digestible regime and providing this for a longer duration of time may accustom the gastrointestinal tract slowly to the change in nutrients between sow milk and solid feed before moving to a less digestible diet. The fact that the beneficial effects did not persist on the long term may have been influenced by the feeding system used. The limitation of a wet feeding system is that the nutrient content of the by-products used may vary considerably (Braun and de Lange, 2004).

Piglets weaned light seemed to benefit the most from weaning at a later age. However, in hindsight it should have been better to have a common weight pre-weaning (i.e. weighing pigs at the same time pre-weaning), and less variable weaning ages to access the effect of weaning age on post-weaning performance. In addition, in the split weaning systems applied previously (Pluske and Williams, 1996b; Vesseur et al., 1997) it was often a combination of weaning age and reducing litter size, but using a nurse sow as suggested in this Chapter would be more practical, though may yield different outcomes. For it to be an economically viable management practise taking sows reproductive performance, space utilisation, and production costs into consideration it should be tested further.

6.4 Scope for future work

From this thesis we have learned that piglets born light hardly consume creep feed during lactation, most likely since the milk form the dam might be sufficient for their reduced growth potential. It is therefore necessary to evaluate management strategies that accommodate the abrupt diet change at weaning better so that piglets keep eating (Dunshea et al., 1999; van der Peet-Schwering et al., 2011; van Oostrum et al., 2016). Previously it has been shown that providing milk replacer during the last week before weaning facilitated the shortage in sow milk by increasing weaning weight (Dunshea et al., 1999; van Oostrum et al., 2016) but providing a milk replacer supplementary to the solid feed provided during the first few days post-weaning may also be beneficial (van Oostrum et al., 2016) with piglets starting to eat sooner after weaning than piglets fed a starter regime (Pluske et al., 1996). This might be especially beneficial for piglets weaned light, with the milk replacer being enriched with specific amino acids such as glutamine or arginine that facilitate gastrointestinal tract development (Kim et al., 2004; Haynes et al., 2009; Wu et al., 2011). These possible solutions can be addressed at a large scale pig unit following a 3 x 3 factorial design with light piglets reared in uniform litters having access to no milk replacer or *ad libitum* milk replacer during the last week before weaning which is provided either as a standard milk replacer or a milk replacer supplemented with glutamine and arginine. Similar treatments could be used post-weaning in which one third of the litters will have access to no milk replacer during the first week post-weaning or access to a milk replacer (though restricted, to limit the incidence of post-weaning diarrhoea) either in its standard form or supplemented with glutamine and arginine.

An alternative approach is to further investigate what makes light piglets different from heavy piglets, which may lead to specific interventions enabling them to catch up growth. For instance, it has been suggested that piglets born light with a poor pre-weaning performance have a lower abundance of lactobacillus (Gaukroger et al., 2018). The latter 'deficiency', may be counterbalanced by supplementation of lactobacillus in the weaner diet, which has recently been able to alter newly weaned piglets intestinal morphology/ barrier function and piglets performance (Wang et al., 2018; Yi et al., 2018).

Further restrictions in the use of in feed antibiotics, zinc oxide, and copper may require an alternative approach post-weaning focusing more on promoting the development of the gastrointestinal tract. Feeding pigs a nutrient dense diet while pigs digestive system is immature or severely damaged may increase the risk of undigested substrate such as dietary proteins to accumulate in the large intestine increasing the proliferation of harmful bacteria, especially after a period of fasting. Dietary fibres have been commonly associated with impaired nutrient utilization, however depending on their properties dietary fibre can actually mediate beneficial effects on the physiological functions of the gastrointestinal tract and gut health (Bach Knudsen, 2001). There is an increasing body of literature on the use of inert fibres in weaner diets and its beneficial effects on increasing feed intake, decreasing the risk for post-weaning diarrhoea, and improving performance (Högberg and Lindberg, 2006; Molist et al., 2009; Gerritsen et al., 2012). However, most of the studies studying the effect on inert fibre during the first week post-weaning focussed on the average piglet but whether the same would apply for piglets born and/or weaned light is currently unknown.

6.5 Conclusions

The findings of this thesis have provided some novel insights in the identification which light piglets might be able to improve postnatal performance and which piglets remain runts. It has become evident that not all light piglets (i.e. light at birth and/ or weaning) are the same and that pig producers need to pay extra attention to the smallest piglet(s) of the birth litter, piglets born with a dolphin shaped head, and piglets born long and thin since these are more likely to remain small. In addition, postnatal environment seems to play a detrimental role in light piglet successfulness to catch up growth pre- and post-weaning, but on the other hand might limit the performance of heavy piglet. Limiting competition within litter, choosing the right foster sow (i.e. mid parity sows), weaning later, and feeding light piglets a starter feeding regime for a longer period of time may all contribute to light piglets improved performance and thus batch efficiency.

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