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Alternative farrowing systems: design criteria for farrowing systems based on the biological needs of sows and piglets

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The construction of a suitable farrowing environment is a continuing dilemma: the piglet's needs must be matched with those of the sow and the farmer during the main phases that constitute farrowing: nest building, parturition and lactation. Difficulties exist in resolving the various conflicts of interest between and within these three parties (e.g. sow v. farmer: space needed for nest building v. space needed to maximise the amount of farrowing accommodation, or sow v. sow: ensuring the survival of the current litter v. maintaining condition for future litters). Thus, the challenge is to resolve these conflicts and design a system that maximises sow and piglet welfare while maintaining an economically efficient and sustainable enterprise. In order to successfully design a farrowing and lactation environment, it is necessary to consider the biological needs of both the sow and her litter. The natural behaviour of the sow has been well documented and very little variation exists between reports of peri-parturient behaviour observed in extensively kept domestic sows and their wild counterparts. The failure for domestication to significantly alter these behavioural patterns provides evidence that they are biologically significant and that the commercial farrowing environment should attempt to accommodate this behavioural repertoire. In addition, the behavioural needs of the piglets, as well as the physiological needs of both sows and their offspring should be considered. This article aims to review the considerable body of literature detailing the behavioural repertoire of sows and their offspring during the different phases of farrowing, and the accompanying physiological processes. The focus is on identifying biological needs of the animals involved in order to synthesise the appropriate design criteria for farrowing and lactation systems, which should optimise both welfare and animal production.

Keywords: pig, nest building, farrowing, lactation, welfare

Implications

Designing suitable farrowing and lactation environments that maximise both sow and piglet welfare, while maintaining economically efficient and sustainable enterprises, is a continuing challenge. It is not unreasonable to consider designing housing systems based on the biological specifications of the animals involved. Therefore, this review documents the considerable amount of literature describing biological needs of sows and piglets. It demonstrates the evolutionary significance and thus the function of certain behavioural patterns that continue to be displayed by domestic animals. Identification of biological needs allows synthesis of appropriate design criteria for farrowing and lactation systems that optimise both welfare and animal production.

Introduction

It is not unreasonable to suggest that agricultural practices in livestock farming systems should be based on the biological needs of the animals involved. However, this is rarely the case, with different managerial constraints (e.g. finance, labour and space) often resulting in a compromise with the animals' biological needs. Perhaps the most prevalent illustration of this occurs during the farrowing and lactation period for the domestic sow. During this period the majority of domestic sows (approximately 70% in United Kingdom, BPEX, 2004; 95% in EU and 83% in United States, Johnson and Marchant-Forde, 2009) are housed in farrowing crates, which are behaviourally and physically restrictive and raise serious welfare concerns. However, the farrowing crate was initially developed to reduce building space requirements, provide safe working access to the piglets, reduce labour input and improve piglet survival (Edwards and Fraser, 1997).

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Piglet survival is one of the most important outcomes of the farrowing period for the three main stakeholders (sow, piglets and farmer); the piglets obviously need to survive, their survival is the key to profitability for the farmer and the sow can measure her inclusive fitness in terms of reproductive success. To facilitate maximum survival there must be co-ordinated expression between behaviours of the sow and piglets, and their interaction with the environment. These interactions are complex, involving a series of conflicts between parent and offspring who have different needs at different stages of farrowing. The conflicts further increase as the needs of the farmer are taken into account. As a result, designing a suitable farrowing environment is a continuing challenge and one that has been the subject of sustained scientific interest (Edwards, 1996; Arey, 1997; Edwards and Fraser, 1997; Wechsler and Weber, 2007).

Designing a suitable housing system based on the biological specifications of the animals concerned involves asking questions about their needs, both behavioural and physiological. The latter include very obvious requirements including provision of appropriate nutrition and climate to ensure maximum growth, development, health and productivity. The former has received a great deal of attention from ethologists, animal welfare scientists and, increasingly, by a concerned public. This has occurred partly because the consideration of 'behavioural needs' when designing housing systems for livestock is often over-looked within the industry, despite many recommendations by scientists to adjust environments to meet these needs (Brambell, 1965; Farm Animal Welfare Council, 1992; Edwards, 1996; European Food Safety Authority, 2007).

Failure to recognise the importance of behavioural needs may actually be counter-productive in terms of maximising animal productivity, since it has long been accepted that the performance of species-typical behaviour contributes to the biological fitness of an animal (Hamilton, 1964a and 1964b). Agriculture has exploited the animals' natural ability to adapt to their environment (Baxter, 1983). Domestication and intensive breeding strategies have resulted in physiological changes in the pig, which have capitalised on the heritability of traits such as litter size and growth rate, in order to have an 'improved' and efficient farm animal. However, the influence domestication has had on the behavioural needs of the pig is less clear, with certain behaviours apparently robust to the changes brought about by intensive selection (Stolba and Wood-Gush, 1980 and 1981). Nest building behaviour in the peri-parturient sow is an example of a behavioural pattern stubbornly being attempted despite, in the majority of intensive agricultural practices, an environment that precludes its natural performance and appears to render its original function unnecessary. The motivation to perform behaviours that on the surface appear unnecessary in a production environment suggests that they still have some biological significance to the animal.

The concept of 'behavioural needs' has been the subject of much debate and detailed scientific analysis (e.g. Dawkins, 1977; Baxter, 1983; Hughes and Duncan, 1988; Jensen and Toates, 1993). For the purpose of this review, the term 'behavioural need' is generally used to describe the need to

perform a specific behaviour pattern whatever the environment and even if the physiological needs which the behaviour serves are fulfilled in other ways (Baxter, 1983; Jensen and Toates, 1993). Possible behavioural needs can be catalogued by identifying species behaviours with important survival value which occur spontaneously in all environments, and by measuring the preferences of animals (Hughes and Black 1973; Dawkins, 1977). However to demonstrate a true need, it should be shown that failure to meet this need results in a compromise in welfare by demonstrating negative consequences when these actions cannot be performed satisfactorily (e.g. performance of abnormal behaviour, physiological stress response or increased incidence of pathology).

Therefore, this review describes which behavioural patterns are displayed by pigs in natural and semi-natural environments during the various phases of farrowing, and then determines whether they have endured domestication and what their functional significance is. To discuss the motivational framework contributing to these behaviours, the physiological processes that accompany them are explored. Further experimental evidence of true biological needs is reviewed, leading to the synthesis of recommended design criteria to accommodate them in a farrowing environment. The next critical step in an overall design process is to address the challenges of accommodating these criteria while taking account of the needs of the farmer. However, the focus of this review will remain the needs of the animals themselves, with subsequent work considering the issues for the farmer.

Nest building phase: nest-site seeking, isolation and building

Sow behaviour and physiology

Nest building is a well-documented behavioural pattern in pigs (Gundlach, 1968; Frädriich, 1974; Stolba and Wood-Gush, 1984; Jensen, 1986), with a recent review highlighting its continued interest in animal science (Wischner *et al.*, 2009). It is an innate behaviour, unaltered by domestication (Jensen, 2002) and displayed by all members of the family Suidae, with the exception of the Common warthog (*Phacochoerus africanus*) which tends to burrow in order to give birth to the young (MacDonald, 2000). An increase in locomotory activity occurs approximately 2 to 3 days before parturition. The sow seeks isolation from the herd and wanders away in search of a suitable nest site. Jensen (1986) reported that expectant sows travelled 2.5 to 6.5 km during the pre-parturient period in search of suitable sites, often building 'mock-nests' during this search, the functional significance of which is still unknown. This heightened period of activity is also evident in peri-parturient sows kept indoors, with reports of expectant sows in 5 m² pens, 'travelling' on average 30 km (Baxter, 1991). Chosen nest sites are often isolated and at least partially enclosed, affording sows a protected nest site while still being able to maintain vigilance for potential approaching threats (Stolba and Wood-Gush, 1984). In addition, nest-site location is considered with excretory and feeding locations taken into account; observations of wild boar report that

dung is found in concentrated, specific areas 'some' metres away from any nest sites (Wiepkema, 1986). Concentrated areas for dunging may serve some territorial function, but also it is important that these areas are away from nest sites to control the risk of disease. Once chosen, a concave depression is created by hollowing out the ground, or by rooting up soil and vegetation into a pile and then rooting a central depression (Hafez *et al.*, 1962; Graves, 1984). Hollowing out the ground involves digging and rooting behaviours, patterns also observed in domestic sows kept in farrowing crates though re-directed towards floors, bars and drinkers (Lawrence *et al.*, 1994). After hollowing out a nest site, branches are gathered to border the hollow before collecting and arranging grass and leaves to line the nest.

Accompanying nest-building behaviour is a range of endocrine changes that have been the subject of a recent review (Algers and Uvnäs-Moberg, 2007) and therefore will only briefly be outlined here. Widowski *et al.* (1990) demonstrated, by injection of prostaglandin (PGF₂ α) into *pre-partum* gilts, which changes in plasma concentrations of prolactin elicited nest-building activities. Further investigations (Castrén *et al.*, 1993a; Damm *et al.*, 2002) have correlated specific nest-building behaviours with specific hormones; time spent carrying and depositing substrate correlated positively with prolactin and progesterone, but negatively with somatostatin concentrations in plasma (Castrén *et al.*, 1993a). Nosing and arranging this substrate correlated negatively with plasma oxytocin (Damm *et al.*, 2002). Therefore, performance and completion of nest building appear to be influenced by both internal and external factors (Jensen and Toates, 1993). There must be a 'switch-off' mechanism because performance of nest building is no longer functional during parturition. Baxter (1983) suggested that udder comfort switches off nesting behaviour, although provision of a comfortable substratum does not abolish the behaviour (Arey *et al.*, 1991). In general, nest-building behaviour abates approximately 4 h before parturition. Oxytocin levels have already started to increase 6 h before parturition (Algers and Uvnäs-Moberg, 2007) and the sow enters a 'quiet phase' before parturition begins.

Functional importance of the nest-building phase

From the detailed descriptions of site choice and construction, as outlined above, the main functions of the nest appear to be protection for piglets from inclement weather conditions and camouflage from potential predators. Thus, its function for wild populations of pigs is obvious, but this does not explain why the action of building a nest should remain so strong in our domestic population of indoor pigs, where the risks from climatic extremes and predation are obsolete. It is possible that the behaviour has persisted simply because of lack of selection against its occurrence, or lack of genetic variation in the control mechanisms within the domesticated population. However, Jensen and Gustafsson (1997) theorized that costly behaviour strategies which are optimal in wild conditions may pay off less in the domesticated situation, and therefore have a negative cost-benefit balance promoting suppression. Nest building is just such a costly

behavioural pattern, involving increased activity and complex construction for as much as 24 h before further energy expenditure during farrowing and lactation. When exploring the importance of behaviours from a life history point of view, a functional aspect of behaviour is based on the contribution that it makes to fitness, as measured by reproductive success (Daan and Tinbergen, 1997). Therefore, we can hypothesise that it is not just the nest that contributes to reproductive success by protecting the offspring, but also the motivation to build and the performance of building that nest. Feedback from building and completing a nest can affect neuro-endocrine regulation of maternal behaviour (Castrén *et al.*, 1993a; Damm *et al.*, 2003; Pedersen *et al.*, 2003; Algers and Uvnäs-Moberg, 2007) during farrowing, with evidence that positive parturient maternal behaviour is influenced by the satisfaction of the nest-building phase (Arey *et al.*, 1991; Jensen, 1993; Damm *et al.*, 2003; Pedersen *et al.*, 2003). For example, several authors have proposed a link between high nest-building activity and reduced risk of crushing (Andersen *et al.*, 2005; Pedersen *et al.*, 2006). The more complete and functional the nest is, the more likely the sow is to end nest building and begin the more somnolent farrowing phase. Sows that continue to display nest-building activity during farrowing are increasing the risk of crushing for their piglets, as well as prolonging farrowing duration with increased risk of piglets being born dead (Baxter *et al.*, 2008). Duration of farrowing has been shown to be longer in sows housed in crates rather than in pens in some (Thodberg *et al.*, 2002; Oliviero *et al.*, 2006), although not all, studies (Cronin *et al.*, 1991; Fraser *et al.*, 1997). It is possible that the inadequacy of nest-building behaviour in crated environments may influence the duration of farrowing and therefore the incidence of stillbirths. The lack of space and substrate when sows are kept in standard farrowing crates precludes feedback from nest-building behaviour and has been shown to constitute a stress for the sow (Lawrence *et al.*, 1994; Jarvis *et al.*, 1997 and 2001; Damm *et al.*, 2003). Further work dissociating the effects of space and substrate demonstrated that space restriction *per se* induced elevated hypothalamic pituitary adrenal (HPA) activity which is deemed indicative of physiological stress (Jarvis *et al.*, 2002). There is also evidence that savaging behaviour is more prevalent in animals housed in farrowing crates (Cronin *et al.*, 1996; Jarvis *et al.*, 1998) and savaging sows are more restless and hyper-responsive to their piglets and environment (Ahlström *et al.*, 2002) than non-savaging sows. It has been proposed that because the restrictive nature of this environment is inadequate to satisfy nest building, the need to nest build may not be 'switched-off'. The sow is thus ill prepared for the somnolent phase of parturition, with potentially fatal consequences for the piglets. Thus despite the absence of offspring at this stage, nest building is arguably a critical phase for piglet survival and consequently remains an evolutionary important behaviour.

Needs-based design criteria for the nest-building phase

From the evidence presented above, it is clear that in order for the species behaviour patterns of the sow to be met

Table 1 Summary of design recommendations to meet the biological needs of sows during farrowing and lactation

Component of system	Biological specification	Recommendations
Space*	Increased activity for nest-site seeking	4.9 m ² (minimum recommendation based on combining two areas the sow can turn around in – see below) ^b
	Hygiene – dunging space	Separate area from nest and feed sites ^a . Interaction with air temperature and floor properties
	Feeding and foraging	Separate area from nest and dung sites ^a
	Turn-around nest space for piglet inspection and gathering behaviour	Floor space = 2.44 m ² , planar space = 3.17 m ² (minimum) ^a . Further research needed for unimpeded turning by the sow
	Lateral lying and parturition	2.79 m ² (minimum) ^a
	Thermal comfort via posture changes	2.44 m ² allows at a minimum getting up and lying down posture changes ^a
	Nest-departure	Separate area from nest site ^b
	Social contact	Full contact only recommended when mixing familiar groups ^b . Space dependent on group size and needs 'clever' design to accommodate avoidance behaviours ^a . Further research needed on 'personal space' for group suckling behaviour
	Gradual separation from piglets and controlled nursing	Separate space unattractive to the piglets ^b . Interaction with air temperature and floor properties
Substrate	Nest-building – carrying and manipulating	2 kg long stemmed straw (minimum) ^a accessible to the sow. Further research needed for alternative substrates with similar properties
	Complete nest	2 kg long stemmed straw and branches (minimum) ^a
	Udder comfort	Further research needed, interaction with floor properties
	Thermal comfort during nest building	Further research needed to determine sow temperature preferences during nest building
	Thermal comfort during parturition	Deep bedding 10 to 12 cm ^a , interactions with floor properties and ambient temperature
	Foraging material	Further research needed on suitable materials and required amount
Walls	Enclosure/isolation of nest	Three solid-sided walls (cul-de-sac) ^b
	Darkness	Dark walls to simulate burrow ^b
	Visual and physical contact with non-litter pigs	Vertical barred area outside nest with void wide enough to allow at least nasal contact between pigs for social integration (minimum) ^b
	Supported posture changes	Solid sloped or vertical walls ^a
	Lack of disturbance	Further research needed to determine benefits of providing a quiet area
Flooring	Nest building – digging, rooting and hollowing	Malleable (e.g. earthen) or solid to accommodate deep substrate ^a
	Nest building and parturition	Solid to accommodate substrate ^a
	Thermal comfort during nest building	Further research needed to determine sow temperature preferences during nest building. Temperature differentials in separate areas allowing choice ^b
	Thermal comfort during parturition	High thermal resistance, for example, rubber matting or deep substrate. Temperature differentials in separate areas ^a . Further research needed for recommendation of localised temperature
	Thermal comfort during lactation	Low thermal resistance, for example, metal. Temperature differentials in separate areas ^b
	Physical comfort – avoiding injury, promoting suckling behaviour	Non-slip surface ^a Minimal abrasiveness, for example, rubber matting or plastic-coated metal ^a Solid to avoid teat injuries ^a
	Hygiene	Slatted area ^a Gradation of floor with slope away from lying area ^b . For example, 10% slope for drainage
		High feed intake
General	Thermal comfort	Ambient temperature 12°C to 22°C ^a , interactions with substrate and flooring
	High feed intake	See space and thermal comfort

^aRecommendations derived from one or more specific references.

^bRecommendations based on synthesising and interpreting the literature reviewed.

*Space calculations based on an 'improved' sow weighing 350 kg.

during this phase, the following criteria should be considered for design: space, enclosure, substrate and suitable flooring. These criteria need elaboration and attempts are made to quantify and summarise them (Table 1).

Space

It is assumed when determining spatial needs for animals, that they are geometrically similar and that the minimum amount of space required is determined by the animal's size

and body shape (Baxter and Schwaller, 1983). This 'body space' can then be added to, to accommodate behavioural requirements. During the nesting phase, space is required to allow the animal to increase its activity, to 'seek' a nest site, build the nest and to have separate nesting, excretory and feeding sites.

Sows normally circle around when constructing the nest, and this may define the minimum space needed for the nest itself. In an experiment looking at the space preferences in different farrowing crates (Phillips *et al.*, 1992), sows consistently preferred the largest width, which permitted them to turn around. This, together with the previously cited evidence for elevated HPA axis activity when turning is prevented, indicates that the minimum space criterion during this phase should allow this behaviour. Quantification of the required space can be derived from the comprehensive work looking at spatial needs of sows in confinement by Baxter and Schwaller (1983) and Petherick (1983a), who used the principle body dimensions of length, height and width to determine the area occupied by any weight of pig. Using these estimates, Baxter and Schwaller (1983) determined minimum space requirements for the 95th percentile sow weight that they measured (238 kg): 1.90 m² (2334 mm long × 810 mm wide × 870 mm high; see Figure 1). The genetic 'improvement' in mature breeding females has resulted in body weights of many commercial multiparous sows between 300 and 350 kg without undue fatness (Whittemore and Kyriazakis, 2006). Such an observation has also been made by other researchers (Moustsen *et al.*, 2004) and in response to Danish sows steadily increasing in size over the last 20 years without farrowing crates changing to accommodate this increase, these authors took detailed measurements of sows entering and leaving farrowing crates in order to provide an improved biological basis for farrowing crate dimensions. The authors provided their minimum recommendations based on the dimensions of the 95th percentile of the population of sows measured, thus hoping to accommodate the largest of the population. Sows in the 95th percentile weighed 352 kg, were 2.00 m long, 0.47 m wide, 0.95 m tall and measured 0.71 m from the middle of the sow's udder to her back (i.e. breadth). From these data, it is evident that minimum space recommendations should be revised for all forms of accommodation by re-calculation based on the 95th percentile of current average weights. For the biological needs of farrowing sows, the above methods described (Baxter and Schwaller, 1983) were used, and assuming linear relationships, Baxter and Schwaller's graph (Figure 1) was extrapolated and it was estimated that an 'improved' sow of 350 kg needs at least 2.44 m² of floor space to get up and lie down comfortably (2654 mm long × 923 mm wide and 968 mm high; Table 1). By adding to the width of this space, a sow would be able to turn around (Robertson *et al.*, 1972). Curtis *et al.* (1989), using Robertson *et al.*'s (1972) data proposed the allometric equation of $15.4W^{0.33}$ (where W = body weight) to determine width for sows to turn around in gestation crates. However, Robertson *et al.*'s calculations were determined based on designing a stall that a sow could not

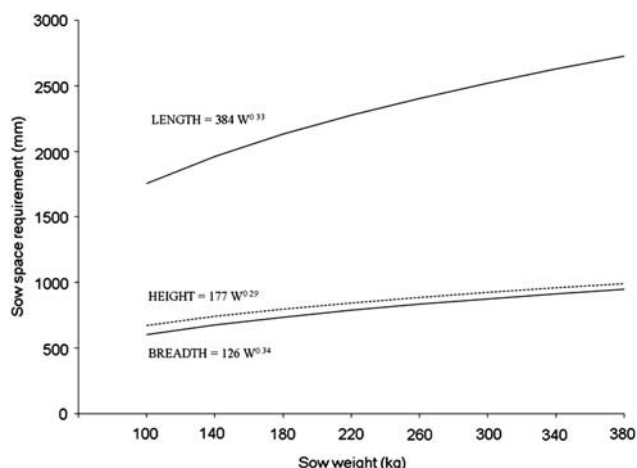


Figure 1 Overall, space requirements of sows (dimensions of pen) expressed over weight (W = body weight). Extrapolated from Baxter and Schwaller (1983).

turn around in and therefore involved the animal squeezing against the stall or crate sides to achieve a turning circle. Without conducting detailed experiments, similar to those undertaken by Baxter and Schwaller (1983), the additional width required for turning around unimpeded by a late gestation sow can only be estimated. Lou and Hurnik (1994) designed an Ellipsoid crate that allowed pigs to turn around (average weight 206 kg) with a floor space of 1.80 m² and a planar space (space at sow's shoulder height) of 2.51 m². If we were to over estimate width needed to turn around and assume the sow needed at least its body length in all planes to turn comfortably, then according to Petherick's calculation (1983a), Lou and Hurnik's 206 kg sow needs a crate planar width of 1.74 m to accommodate a comfortable 360° turn. In fact, 1.20 m was provided and sows were able to turn around. Adjusting for the difference between this expected width and actual width of 0.54 m, when applied to a 350 kg sow, results in a planar width of 1.53 m and a planar area of 3.17 m² (sow length × planar width) for turning around, thus giving our current, minimum design criterion for space (Table 1).

In addition to turning around, the sow species behaviour patterns suggest requirement for additional space to increase activity and separate excretion and feeding areas. Overlap of the excretory area with either the nest or feeding area will result in impaired hygiene and is likely to increase the risk of adverse health consequences in this and subsequent lactation stages. In addition, overlap of the nest and feed area will increase activity and divert focus of attention within the nest, thus increasing risk of piglet mortality after farrowing. Evidence regarding preferred excretory and lying sites for sows is rare (Wiepkema, 1986), which is unsurprising given the lack of choice presented to the majority of farrowing sows housed in crates. However, studies looking at gilts (Damm and Pedersen, 2000) and piglets in the farrowing environment showed that in general pigs, when given the opportunity, will keep separate areas for excretion and resting (Watson, 1978; Petherick, 1983b). Without detailed work determining the area needed to satisfy feeding

and dunging needs, we can only estimate this based on the calculations already described. Space required for feeding can be described as 'static', with the requirement that the sow has to be able to stand up and feed. Therefore, as described above, a 350-kg sow would require 2.44 m² of floor space for feeding. In addition, the sow needs to be able to exit the feeding area, however space provided for nesting or excretion could accommodate this requirement. Based on the above calculations, floor space required for a 350-kg sow to have a separate excretion site, in which it can turn around would be the same amount described for nesting (i.e. at least 2.44 m² floor space and 3.17 m² planar space – Table 1). However, it is likely to be the properties of the space, not just the quantity that will determine suitability for meeting needs. For example, pigs prefer to excrete in spaces away from feeding and nesting sites (Baxter, 1982). In addition, excretory areas can be created by providing temperature differentials, whereby intended dunging areas are cooler (Randall *et al.*, 1983) than lying areas (Table 1). With these factors in mind, it is possible that quantity of space could be reduced if substituted by attention to detail and clever design.

Enclosure

In tests looking at the choice of nest site, Hunt and Petchey (1987) demonstrated that sows always chose farrowing locations that were inside, or against a solid wall, never out in the open. This matches the choices of sows under natural and semi-natural conditions (Stolba and Wood-Gush, 1984) where 40% chose total enclosure and 89% chose partial enclosure. However, the amount of enclosure needed to satisfy nest-site choice is still not clear. Providing nest sites that are enclosed on three sides with a side open or partly open would facilitate isolation and vigilance for potential threats (Table 1). Under natural conditions, the nest often includes a roofed area of vegetation, providing protection from inclement weather as well as concealment from potential predators. There are contradictory reports as to the benefits of a roof under indoor farm conditions. Phillips *et al.* (1991) found that providing a 'roof' had no positive influence on site choice between totally enclosed, partially enclosed or open crates and that enclosure was preferred more by younger sows. When a crude form of enclosure was given to animals farrowing in crates by providing a Hessian roof (Cronin and Vanamerongen, 1991), maternal behaviour was influenced positively and it was suggested that the make-shift roof offered a sense of nesting completion for the sow. The crates in this experiment had no further enclosure, and therefore it is possible that the influence was not roof specific.

Substrate

Substrate manipulation, as well as enclosure appears to contribute to perception of nesting completion and, in preference tests with both elements offered, sows made a choice based on the pre-formed nest sites that also offered sufficient quantity of straw to satisfy nest-building behaviour (Arey *et al.*, 1992). Such has been the case in other nest-building species; in farmed mink, for example, when provided

with an artificial nest (nest box), kit survival and vitality was improved and maternal stress *post partum* was reduced (Malmkvist and Palme, 2008). However, there appeared to be greater benefits from providing an artificial nest in conjunction with access to straw, with less variable duration of parturition displayed by these animals with the enriched nests. Hutson (1988) tested a limited number of sows and gilts in an operant conditioning experiment and, based on a low motivation for sows to lift a lever 10 times to obtain 1 kg of straw, it was concluded that straw is unimportant to prepartal sows. However, this claim is unsupported by the majority of other research in this area (Arey *et al.*, 1991 and 1992; Arey, 1992; Damm *et al.*, 2000). Arrangement of nest-building material provides feedback to the expectant sow and, without suitable feedback from this activity to signal that nesting is complete, some sows may continue to be motivated to nest build even during farrowing (Thodberg *et al.*, 1999; Damm *et al.*, 2000). This constitutes a risky situation for the newborns and therefore is counter-productive for reproductive success.

Thus, substrate is important, but the unresolved issue is quantifying the necessary amount and type of substrate. There have been reports of sows making very complex nests outdoors, with 255 kg of substrate in one nest (Zanella and Zanella, 1993). Such extreme quantities are impractical and most likely unnecessary under indoor conditions. The complexity of nesting substrates can influence behaviour; Damm *et al.* (2000) demonstrated that gilts given branches and straw were better able to construct a 'complete' nest than gilts only provided with straw. Arey *et al.* (1991) gave two groups of sows sandy depressions with straw available from a dispenser and absence or presence of pre-formed nests with 23 kg of straw on the floor. The first group removed 23 kg of straw and used it for nest building, while the latter group removed 9.5 kg in addition to the 23 kg already pre-formed. Recent work by Damm and Pedersen (L Pedersen, personal communication) has recorded the amount of substrate carried by sows during the nest-building phase and they have recommended that a minimum of 2 kg of long-stemmed straw be provided to all sows *pre partum* as nesting material (Table 1). Alternative nesting materials have been studied (Widowski and Curtis, 1990), with recommendations that providing a cloth tassel that animals can pull, tear and manipulate may also provide benefits even if the material cannot result in the building of a suitable nest. This is particularly relevant for animals kept in crates, as the majority of the tassel remains at the front of the crate, where sows can continue to access it, whereas straw is often pushed to the back of the crate during nest building, and becomes unavailable (Table 1).

Flooring

Additional preference tests have been performed on the properties of the floor, with 100% of sows choosing to farrow in an earthen pen site that could be hollowed out compared to a concrete floor (Haskell and Hutson, 1994). It is possible that this earthen site offered qualities in addition

to its deformability, including greater udder comfort for the sow or lower thermal conductivity, and clarification of which properties are of importance needs further research. If physical comfort is a key aspect, then quantity of substrate on the floor or area of 'comfortable' flooring should accommodate a sow lying laterally for parturition. Arey *et al.* (1991), in their pre-formed nest experiments already described, noted that 100% of sows farrowed in the sandy depression, potentially because of similar, 'comfortable' qualities. Thodberg *et al.* (1999) suggested that the sand provided in their experiments gave important feedback, in addition to that provided by the substrate available. Thus, flooring with malleable properties to accommodate nest building activities is recommended (Table 1). Thermal comfort is also likely to be a consideration of the nest site and, in choice experiments offering sows a concrete floor or a mat floor with varying amounts of straw, sows appeared to show a preference for flooring that offered the greatest thermal resistance (the mat with the most amount of straw – Hunt and Petchey, 1987), thus limiting the loss of heat via conduction. However, when sows were offered a heated (34°C) or non-heated floor space there was no difference regarding their choice of farrowing area (Pedersen *et al.*, 2007). Thus, further and more detailed investigations are needed on temperature preferences of nesting sows (Table 1).

In addition, the drainage properties of the floor, as well as the provision of space, will facilitate hygiene. Perforated or slatted flooring has been shown to have higher hygiene than solid floors (Rantzer and Svendsen, 2001), however there may be negative consequences from such flooring regarding injury to both piglets and sows (see later section). Defined areas with different floor types and gradation in solid flooring to facilitate pen hygiene by creating a drainage slope, would offer a compromise to satisfy these needs (Table 1).

Parturition, early lactation and nest-occupation

Sow behaviour and physiology

Sow behaviour during this phase is characterised by prolonged lateral lying and udder exposure. Despite only rudimentary maternal care during parturition in this species, sows in semi-natural environments will get up during parturition to inspect their offspring, making nose-to-nose contact before rooting the nest to move piglets out of the way and then resuming lateral lying (Gundlach, 1968; Jensen, 1986). Reactivity patterns of farrowing sows have been described by several authors (Jensen, 1986; Jarvis *et al.*, 1999; Pedersen *et al.*, 2003), with sow's responsiveness being highest in the first 2 h of parturition followed by a prolonged (approximately 6 h) non-responsive phase and then, in conjunction with general activity, responsiveness returns. This pattern is accompanied by endocrine changes (Algers and Uvnäs-Moberg, 2007), but is also influenced by the environment. During farrowing an increase in plasma oxytocin concentrations, promoting uterine contraction for piglet expulsion (Castrén *et al.*, 1993b), also results in continuous let-down of colostrum from the teats. Feedback from the udder, stimulated by massage from piglets, also increases oxytocin concentration and milk let-down

(Algers *et al.*, 1991). Colostrum availability declines exponentially during the first 24 h of secretion, before changing to milk by 30 h *post partum* (Le Dividich *et al.*, 2005). In the early stages of the lactation period, sows generally do not leave the nest site. Observing sows under semi-natural conditions, Jensen (1986) reported that for the first 2 days *post partum* the majority of sows spent 90% of their time in the nest, with the remaining 10% of the time occupied by brief foraging ventures outside. During this nest-occupation phase, sows will spend a large part of the time initiating suckling bouts and nursing their piglets at 30 to 70-min intervals.

Piglet behaviour and physiology

Almost immediately after birth the piglet will start udder and teat seeking behaviours, relying on a mixture of visual, auditory, olfactory and tactile stimuli (Jeppesen, 1981; Morrow-Tesch and McGlone, 1990; Parfet and Gonyou, 1991). Welch and Baxter (1986) suggested that the thermal and tactile properties of the udder are unique in the extrauterine environment, offering salient characteristics similar to those of the intrauterine environment, and therefore highly attractive to the newborn piglets. Colostrum flow is continuous during parturition and piglets have access to relatively plentiful colostrum for approximately 12 h after the birth of the first piglet (Fraser, 1980), before cyclical let-down (approximately every 30 min) of colostrum begins. The diffuse epitheliochorial nature of the porcine placenta means that piglets are born without immune protection, having to acquire maternal antibodies through ingesting colostrum (Gaskins and Kelley, 1995). To acquire passive immunity the small intestine of the newborn piglet undergoes dramatic functional changes immediately *post partum* (for review see Xu *et al.*, 2000). During the first day of life, the neonate's small intestine has the ability to absorb macromolecules, such as intact immunoglobulins (IgGs), across the brush border membrane. The capacity for macromolecule absorption diminishes as early as 24 h (Rooke and Bland, 2002) and is usually complete by 48 h *post partum*, a phenomenon generally referred to as gut closure (Gaskins and Kelley, 1995). Though having an early time window for gut closure limits the time for IgG absorption, it also reduces the chances of pathogens entering the gut and subsequent disease risks. It is noteworthy that the earliest time for sow nest-site departure coincides with gut closure and thus the cessation of passive immunity acquisition by the piglets.

To achieve a high intake of colostrum, gain warmth and establish a teat order, piglets prefer to lie close to the udder during the first 24 h of life. However, there is a trade-off between udder access and the risk of being crushed by the sow. This risk is enhanced when a piglet's energy reserves are low and Weary *et al.* (1996) concluded that crushings are at least partly the result of the nutritional challenge facing piglets. They found that piglets with slow weight gain spent more time in risky areas underneath their sitting or standing mother. Crushing predominantly occurs as the sow makes a posture change from standing to lying or when rolling (Damm *et al.*, 2005; Weary *et al.*, 1998) and the risks associated

with these posture changes are dependent on the environment in which the sow farrows and her maternal behaviour. In a study by Wechsler and Hegglin (1997), it was demonstrated that the quality of the sow's pre-lying behaviour influenced the risk of crushing. Sows that lay down vertically rather than flopping, and those that paid attention to their piglets' location in the nest prior to lying down, had fewer crushed piglets in their litter. Although this study was limited to a small sample size of 11 sows, similar results have been described by other authors (Signoret *et al.*, 1975; Blackshaw and Hagelso, 1990) with sows observed to root through the straw with their noses and group their piglets before lying down considered the more careful mothers.

Newborn piglets are also susceptible to hypothermia as, from the moment they are born and make the transition from the intrauterine and thermoneutral environment to the extrauterine environment, they experience a dramatic reduction in ambient temperature (by approximately 15°C to 20°C – Herpin *et al.*, 2002). Consequently, the lower limit of the thermoneutral zone (the lower critical temperature – approximately 34°C Mount, 1968) is not achieved, and the piglet is at risk of becoming chilled. The physiological immaturity of the newborn piglet contributes to its vulnerability; it is born with very little insulating adipose tissue and no brown fat (Herpin *et al.*, 2002), so can only fuel heat production and increase its core body temperature by mobilising energy reserves, present as glycogen and fat and then catabolism of its skeletal muscle. Glycogen reserves present in muscle are low and depleted quickly (Herpin *et al.*, 1992) and most fat that is present is not available for mobilisation as it is structural fat (Herpin *et al.*, 2002). Catabolism of skeletal muscle is also limited as the process of protein oxidation is poorly developed in the neonatal pig (Schmidt and Herpin, 1998). In addition the domestic, typical 'pink' piglet has lost much of the physical protection from pelage that its wild ancestors (i.e. wild boarlets) have (Foley *et al.*, 1971). The need to preserve homeothermy is therefore closely linked to the need to ingest colostrum, and the post-birth drop in body temperature is only reversed once this is achieved (Noblet and Le Dividich, 1981; Baxter *et al.*, 2008).

After farrowing, as continuous colostrum supply switches to more cyclical milk let-downs every 30 to 70 min (Fraser, 1980; Lewis and Hurnik, 1985), a teat order develops, with strong individual teat fidelity. Suckling not only fulfils basic physiological needs but also assists in establishing bonds between mother and offspring. As with teat-seeking behaviour, recognition appears to involve a mixture of olfactory, auditory and tactile stimuli. Odour cues are important with respect to individual teat recognition by the piglets (Jeppesen, 1982; Morrow-Tesch and McGlone, 1990). Auditory cues are most evident before and during suckling, or in distress situations. The sow commences suckle grunting before let-down, signalling to the piglets to gather at the udder (for review see Fraser, 1980). Further to these olfactory and auditory stimuli, tactile stimuli are evident as the piglets display pre- and post-let-down suckling massage of the udder, and piglets are often observed post-let down going to the sow's head to make nose-to-nose contact.

Functional importance of behaviours during the parturition and nest occupation phase

Once the piglets are born, they face a number of significant challenges arising from an unpredictable mother and environment. In order to survive piglets must get to the udder, show vigour in acquiring and maintaining a functional teat and thus ingest vital colostrum to aid energy balance, preserve homeothermy and promote immune-function (Baxter *et al.*, 2008). This requires effective synchronisation between behaviours of the sow and her piglets. The functional importance of neonatal piglet behaviours is self-evident from the description of physiology. One of the most frequently reported piglet mortality syndromes is hypothermia and starvation leading to piglet lethargy, subsequent crushing and death (English and Morrison, 1984; Weary *et al.*, 1996; Edwards, 2002). However, thermal comfort represents one of the areas where there is potential for parent-offspring conflict. The temperature zone of thermal comfort for a sow is between 12°C and 22°C (Black *et al.*, 1993), and at temperatures above 22°C, adult pigs are increasingly susceptible to heat stress. Heat stress affects lactational output by lowering feed intake, thus contributing to decreased piglet weight gain and increased sow lactational weight loss (Stansbury *et al.*, 1987). In contrast, the small size and immature physiology of the newborn piglet results in a lower critical temperature of 34°C (Herpin *et al.*, 2002). Thus, a compromise must be reached to balance these conflicting needs. Investigations of the thermal properties of nest sites in 'natural' farrowing conditions show that the nests are robust to climatic extremes (Algers and Jensen, 1990), maintaining an average temperature in winter of 20.3°C despite outdoor temperatures averaging –1.5°C. Thermal image data from commercial outdoor huts, taken at the time of farrowing, showed that hut temperature averaged 14.7°C, whereas within the deep straw bedding and at the udder of the sow, temperature averaged 31.5°C (Baxter *et al.*, 2009). This evidence further supports the functional role of nest building behaviour by domestic sows to balance thermal needs and the functional significance of a nest during parturition and nest occupation.

Movement by the sow during farrowing is risky for the piglets, with more passive maternal behaviour thought of as positive to allow safe udder access for the piglets. However, under natural and semi-natural conditions sows will get up, turn around and inspect their piglets (Gundlach, 1968; Jensen, 1986). The functional significance of this was questioned by the authors because of the risks involved. However, in a more natural setting, early interaction with the piglets may enhance the mother–young bonds and litter recognition before returning to the herd. This factor is unlikely to be as important in a conventional indoor situation, where dam and offspring remain together alone until weaning. However, recent work suggests that interaction with piglets is important to allow positive maternal behaviour to develop; Andersen *et al.* (2005) demonstrated that 'non-crushing' mothers were observed to spend more time making nose-to-nose contact with piglets before lying down, as well as reacting to a piglet distress call by making contact with piglets sooner than 'crushers'.

Auditory cues regulate social and nutritional relationships between mother and offspring (Puppe *et al.*, 2003) and not only do the rhythmic vocalisations of the sow during nursing assist with synchronous feeding behaviour, they also provide an auditory 'fingerprint', unique to the sow, that the piglets can use for recognition of their own mother. It appears that, even within the first few hours after birth, piglets are rapidly learning the unique composition of vocalisations by their mother (Walser, 1986). Work by Horrell and Hodgson (1992) showed that, as early as 36-h old, piglets were able to recognise the vocalisations of their own mother over those of an alien sow.

Tactile stimulation performed by the piglets at the udder fulfils several functions; suckling massage releases prolactin that assists with adapting maternal physiology to cope with lactation (Algers *et al.*, 1991) and, dependent on the time spent massaging, increases the teat milk yield for the next suckling – the 'restaurant hypothesis' (Gill and Thomson, 1956; Algers and Jensen, 1985). Nose-to-nose contact between piglet and sow post let-down is thought to signal need and reaffirm bonds and recognition. Recognition of their own mother is an important task for the newborn piglet since pigs are social animals, naturally living in groups where mothers, often themselves related, will synchronously give birth to multiple young (Gundlach, 1968). Frequencies of these nasal contacts under semi-natural conditions were found to decrease substantially with time after farrowing and to stabilise to a low level on day six *post partum* (Stangel and Jensen, 1991), coinciding with the average nest abandonment day also observed by these authors. Under more intensive conditions, it would seem that this recognition is not warranted, as sows and piglets generally do not mix before weaning. Thus, it can be hypothesised that this nose-to-nose contact behaviour has persisted more as a way of signalling need and reaffirming a bond to solicit milk.

Needs-based design criteria for the parturition and nest occupation phase

The needs of the sow during farrowing depend on the satisfaction gained from the nest-building phase. A quiet, enclosed area with a suitable and complete nest should result in a sow that performs increased lateral lying during farrowing (Jarvis *et al.*, 1999). The needs of the piglet during this crucial time are more complex than those of the sow; however, they are invariably linked to the behaviour of the sow. Given that the satisfaction of the nest-building phase directly influences the parturition phase, the criteria for nest building apply here: suitable space, enclosure, substrate and flooring. The evidence presented above suggests that thermal comfort, physical protection of piglets via suitable walls and substrate, as well as lack of disturbance are additional attributes to consider.

Space

Static space required during parturition can be calculated in a very simple manner, with the sow needing to lie laterally and have enough space to facilitate birth and suckling for the

piglets (Table 2). Petherick (1983a) developed an equation for determining space needed for a pig to rest on its sternum or be fully recumbent (Figure 2). Using these equations and assuming that the sow is static while giving birth, a 350-kg sow lying laterally is 2.07-m long and 1.08 m in depth and occupies 2.24 m² of space. In addition, there needs to be dynamic space for the piglets to be born safely and to walk around the sow to access the udder and suckle colostrum.

Using the same equations but applying these to an optimum weight piglet of 1.6 kg (Roehe and Kalm, 2000), whose dimensions would be 0.35-m long and 0.07-m wide, a 350-kg sow giving birth to 1.6 kg piglets would require a minimum floor space of 2.79 m² (Table 2). This is based on a rather crude assumption that in order for the piglet to negotiate access to the udder the existing area allowing lateral recumbency for the sow must now accommodate a piglet being born and then walking around its mother. Therefore, the nest-size space is based on the following equation:

$$(\text{Sow length} + \text{piglet length}) \times (\text{sow lateral width} + \text{piglet ventral width})$$

Suckling space should also be considered, at farrowing and during lactation. Work already described above providing body dimensions of farrowing sows (Moustsen *et al.*, 2004) was added to, to provide body dimensions of suckling piglets (Moustsen and Poulsen, 2004a); these authors recommended that the width between the sow's udder and any solid surface should be a minimum of 0.50 to 0.60 m to allow 4 to 5-week-old piglets to all suckle comfortably in the space envelope between the sow's front and back legs when lying laterally. Thus, the conclusions drawn from these combined data are that the depth would need to be between 1.21 and 1.31 m for lateral lying and comfortable suckling throughout lactation (Table 2).

From the evidence presented above the sow also needs to be able to turn around and inspect her piglets, as well as perform piglet gathering or grouping behaviour before lying down. Therefore, similar calculations for the nest-building phase can be made and a 350 kg sow should have a nest-size that facilitates turning (Table 1). Recent work by Weber *et al.* (2009) compared piglet mortality in loose-housed systems in Switzerland in relation to pen size. They and other groups observed no difference in mortality levels in crateless pens measuring over 5 m² compared with crated accommodation (Cronin *et al.*, 2000; Weber *et al.*, 2007), suggesting that where studies have shown higher mortality in crateless pens than in crates (Blackshaw *et al.*, 1994; Marchant *et al.*, 2000), this was a result of the pens being under 5 m². Consequently, Weber *et al.* (2009) suggest this should be the minimum space requirement for unimpeded piglet gathering behaviour. However, further research is needed to give accurate figures for both comfortable turning and unimpeded gathering behaviour. In addition, during the nest occupation phase, the space needs to facilitate hygiene to avoid detrimental effects on piglet health. Therefore, the

Table 2 Summary of design recommendations to meet the biological needs of piglets during farrowing and lactation

Component of system	Biological specification	Recommendations
Space ^c	Parturition	Length of sow and piglet (2.42 m) × width of sow lying laterally and ventral piglet (1.15 m) = 2.79 m ² (minimum) ^a
	Udder access for suckling throughout lactation	Depth of sow (0.71 m) + length of 4 to 5 week old piglets (0.50 to 0.60 m) = 1.21 to 1.31 m (minimum) ^a
	Protection, safe lying area for parturition and nest occupation	Separate space inaccessible to the sow e.g. 0.80 m ² per 10 to 12 neonates ^a
	Protected lying area during lactation	0.97 m ² (minimum) – 2.32 m ² (maximum) for 14, 4-week-old piglets ^a
	Area for feed trough to introduce creep feed Hygiene	Provide in area inaccessible to the sow, interacts with above ^b Separate area for dung site, interacts with flooring ^a
Substrate	Foraging, nutritional development Enrichment, social development	Earth-like materials (e.g. peat) ^a Further research needed on quantity. Novelty requires fresh input daily. Complex materials (e.g. branches) preferred ^b
	Thermal comfort during parturition	2.5 cm of straw ^a , interacts with flooring
	Physical comfort	Further research needed, interacts with thermal comfort and flooring properties
	Protection	Deep bedding – 10 to 12 cm ^a , interacts with flooring
Walls	Protection from sow posture changes Social contact (visual and physical)	Escape zones at all pen walls ^b Vertical barred area (minimum) ^b . Further research needed to determine best method to mix pre-weaning.
	Hygiene	Solid walls (at least at bottom of penning) separating other litters during first 7 days of life ^b
	Thermal comfort	Solid walls in lying area of material to limit heat loss via radiation ^b – interacts with substrate and flooring
Flooring	Thermal comfort during parturition and first 24 h of life	High thermal resistance ^a – for example, rubber matting or deep substrate (see above) or under-floor/localised heating (see General)
	Thermal comfort during lactation	High thermal resistance ^b – for example, rubber matting or deep substrate (see above) or under-floor/localised heating (see General)
	Physical comfort – avoiding injury, promoting suckling behaviour	Solid flooring with minimal abrasiveness and well maintained (e.g. rubber matting or specialised screed with non-slip properties), interacts with substrate
	Protection from fatal crushing by the sow Hygiene	Malleable flooring ^b interacts with deep substrate Slatted flooring with void width no more than 10 mm and rounded edges ^a . Interacts with temperature (see General)
General	Health – treatment for injuries, vaccines, etc. Promote weaning, reduce nutritional stress and encourage increased feed and water intake	Safe area for handling required to ensure piglet health needs, interacts with space ^b Suitable solid food, inaccessible to the sow – interacts with space and substrate. Provide feed tray with sufficient space to allow social facilitation ^a . Provide water drinker with upward angled bite nipple close to floor ^a
	Thermal comfort	Localised heat source set at thermo-neutral temperature (e.g. 34°C at birth) – interacts with substrate ^a
	Hygiene	Temperature differentials to encourage dunging outside of nest site – interacts with flooring ^b

^aRecommendations derived from one or more specific references.

^bRecommendations based on synthesising and interpreting the literature reviewed.

^cSpace recommendations for an 'improved' sow weighing 350 kg and an 'optimum' birth weight piglet of 1.6 kg

space has to provide a defined excretion area away from the nest site, as described in the nest-building phase (Table 1).

Protection

Protection for the newborn piglet is paramount to its survival since crushing by the dam, as either proximate or ultimate cause, is the most frequently recorded reason for mortality. Though, under more natural settings, sows and piglets occupy the same space in the nest, under commercial indoor housing conditions it is generally accepted, and indeed recommended (Defra publications, 2003), that 'a solid and

dry lying area' away from the sow be provided so that the piglets can 'all rest at the same time' and be protected (see also CoE, 2001). This area, often referred to as a creep, also makes it possible to provide different microclimates, as well as separate nutritional provision (see later section) and facilitates easier access for health checks and husbandry procedures. However, it requires additional space (Table 2). Detailed work in Denmark (Moustsen and Poulsen, 2004b) studied piglet dimensions (weight, length, height and depth) in different postures, with the average snout to tail length of 4-week-old piglets measuring 0.56 m, their shoulder width

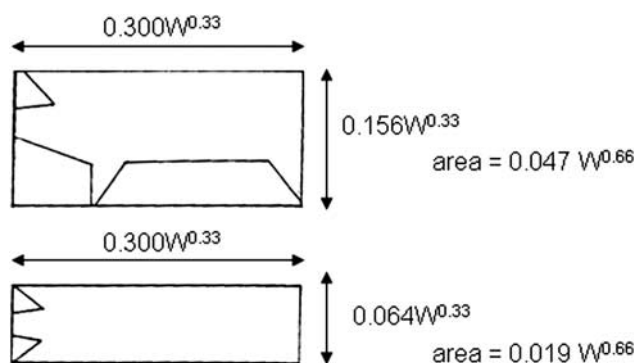


Figure 2 'Pigtographs' by Petherick (1983a) showing the space requirements for a pig resting fully recumbent or on its sternum (W = body weight in kg; area in m^2).

0.13 m and their depth measuring 0.14 m. Thus, these authors determined that to accommodate 10 to 12 piglets until weaning at 4 weeks of age, a creep should be no less than $0.80 m^2$ (Table 2). Further investigations by these authors have resulted in recommendations that each piglet, when weaning at 4 weeks of age should have a solid, dry area of $0.069 m^2$. Therefore, recommendations for high litter sizes of 14, 4-week-old piglets would require an area of $0.97 m^2$ (Table 2) available to them (V. Moustsen personal communication). However, such minimum recommendations only allow resting in a ventral position. To allow full lateral recumbency, which is a position increasingly adopted as the piglet gets heavier and older (Eckel *et al.*, 2003), $0.166 m^2$ /piglet would be needed (Table 2). It is possible that such lying areas do not have to be provided solely in the creep; protective space (e.g. underneath sloped walls) may accommodate a number of resting piglets as they get older and heavier. At this time their thermogenic abilities are well developed (Herpin *et al.*, 2002) and therefore the need for all piglets to simultaneously access a heated area may decrease.

Deep bedding (10 to 15 cm depth) also has protective properties (Table 2); it is a malleable, non-uniform mattress cushioning sow posture changes and offering a buffer to piglets from fatal crushing (Baxter *et al.*, 2009). This is most likely more effective when the flooring is also malleable (e.g. earth, sand; Table 2) and under outdoor conditions piglets observed to be crushed by their mothers have appeared up to 4 h later from underneath the sow relatively unharmed and have survived to weaning (E Baxter, unpublished observation).

The care and control with which the sow lies down will influence piglet survival, and providing sows with a supportive surface to lean against during their descent has been shown to reduce crushing (Baxter, 1991; Marchant *et al.*, 2001). In the latter study, 89% of sows preferred to use sloped walls, farrowing rails or creep sides to lie down against rather than descend unsupported. Damm *et al.* (2006) enhanced this work by discriminating which was the most preferred choice of supportive structure. They concurred that the majority preferred support regardless of its form, but found that sows preferred solid sloped or vertical walls over farrowing rails (Table 1). Moreover, a recent survey by Weber *et al.* (2009)

showed no significant influence of the presence of piglet protection bars on piglet losses. The traction and comfort of the floor will also influence lying behaviour, thus protection for the piglets (Damm *et al.*, 2005), as well as the health and welfare of both sow and piglets (Boyle *et al.*, 2000). In the latter study, Boyle *et al.* (2000) demonstrated when rubber mats were given instead of metal slats sow comfort was improved and slipping reduced (Table 1).

Thermal comfort

As stated previously, thermal comfort represents an area of potential parent-offspring conflict and the design challenge involves balancing the dichotomised needs of the sow and piglets. Although sows are at risk from heat stress at temperatures above $22^\circ C$, recent evidence suggests that sows show a preference for warmer areas in the immediate *post-partum* period (Phillips *et al.*, 2000; Pedersen *et al.*, 2007) and certainly will avoid metal flooring, potentially because of the cooling properties of this floor type (Table 1). Both Pedersen *et al.* (2007) and Phillips *et al.* (2000) found the majority of sows chose to lie on floors with temperatures of $34^\circ C$ and $35^\circ C$, respectively, *post partum* and for the following 3 days, after which there was a pronounced change to preference for the cooler floors (Phillips *et al.*, 2000). In both cases, in order to facilitate choice, the sows were loose-housed and thus posture changes to regulate their temperature were possible. Further research is necessary before recommending a floor temperature of $35^\circ C$ as a design criterion in all circumstances, as sows might develop heat stress, particularly if their mobility is restricted. Even if mobility is not restricted, as in loose-housed environments, if sows do not have access to cooler areas they can develop heat stress, as evidenced by Malmkvist *et al.* (2009). These researchers heated the floor fully to $34^\circ C$, limiting behavioural thermoregulation and resulting in increased plasma levels of cortisol and ACTH for sows housed in this treatment.

To meet the thermal needs of the piglet, while safeguarding sow comfort, the provision of facilities to create a microclimate are important. Within the nest area, provision of bedding plays an important role. Deep bedding slows heat loss, having a thermal resistance 11 times greater than that of concrete slats and 22 times greater than solid, wet concrete flooring (Wathes and Whittemore, 2006). Mount (1967) demonstrated that piglets in contact with a concrete floor lost 40% more heat than those in contact with 2.5 cm of straw. Deep bedding will also help reduce evaporative heat loss by speeding the physical removal of placental membranes. In the absence of deep bedding, an artificially heated creep area of suitable size (see above) can provide an effective microclimate provided that piglets can be attracted to use this area at an early age. Creep designs have attempted to exploit the piglet's attraction to the stimuli of warmth and softness (Welch and Baxter, 1986) by providing temperature differentials (Burri *et al.*, 2009; Vasdal *et al.*, 2010), water beds (Ziron and Hoy, 2003) or simulated udders (Lay *et al.*, 1999). However, most piglets prefer to lie at the udder of the sow for at least 24 h after parturition. Nevertheless, a creep area, to provide an effective microclimate

either using heat lamps or heat mats, is recommended (Table 2). If this is not provided then the minimum recommendations to facilitate thermal comfort for piglets at this stage would be provision of straw at a depth of at least 2.5 cm (Table 2), given an ambient room temperature no greater than 22°C to avoid sow heat stress (Table 1).

Lack of disturbance

Isolation of the nest site selected under natural conditions minimises risk of disturbance. There is evidence that disturbance during parturition will negatively influence oxytocin levels (Lawrence *et al.*, 1992). Certainly, the length of the non-responsive phase after the birth of the last piglet may depend on how quiet the nest site is, and may influence subsequent restlessness of the sow and risk of piglet crushing. Analysis of data from both indoor and outdoor farrowing systems indicates that group farrowing in more confined circumstances significantly increases mortality risk (Edwards and Fraser, 1997; Marchant *et al.*, 2000). Sow reactivity is a potential risk factor; though sow responsiveness to the distress calls of a piglet have been considered positive maternal behaviour (Wechsler and Hegglin, 1997; Andersen *et al.*, 2005), when sows farrow in individual pens which are in close proximity, they may respond vigorously to distress calls from outside their own nest, to the potential detriment of their own piglets. Together with disturbance from external activities on the pig unit, this consideration indicates a requirement for further research to evaluate the benefits of a quiet nest site. The degree of enclosure afforded to the nest site will influence disturbance levels; however, clarification of the relative importance of visual and auditory isolation is needed (Table 1).

Nest departure and social integration

Sow and piglet behaviour and physiology

At this stage, in mid lactation, sow and piglet behaviours are reasonably well aligned, with both mother and offspring sharing similar biological goals. Thus, in this section, their behaviours are described together. In a free-range system, piglets will leave the nest site before they are ready for weaning. Gundlach (1968) reported that piglets stayed close to the nest for 7 to 14 days *post partum* and, after venturing out, often returned to suckle and re-establish attachment with the sow via piglet-initiated nose-to-nose contacts. Strategies of newborn ungulates are usually divided into two types; 'hidiers' and 'followers' (Lent, 1974). Hidiers tend to stay in vegetation and await a parental signal to leave this protected site, whereas followers stay close to their parent(s). As a result of building a nest, pigs have generally been described as hidiers (Lent, 1974). However, Jensen and Redbo (1987) described piglets at the time of nest-leaving as entering an intermediate phase in their behavioural development as they change from a 'hider' to a 'follower' strategy. On adventures out of the nest, piglets will follow their mother during foraging bouts. Sows will increase these foraging bouts as lactation progresses and the energy demands become more intense, causing sows to mobilise

their body reserves (Quesnel and Prunier, 1995) and switch from an anabolic to a catabolic state (Valros *et al.*, 2003). Milk production then peaks by the 3rd week in lactation, before gradually declining (Elsley, 1971). When accompanying the sow on ventures out of the nest, piglets mix with other litters and engage in important social behaviours before returning to the nest to suckle. Petersen *et al.* (1989) identified an age-dependent high motivation for piglets to integrate or establish social bonds outwith their litter. Piglets were observed to interact with non-litter mates of the same age between 2 and 6 weeks *post partum* and thereafter they interacted with other group members.

Functional importance of behaviours during this phase

Nest departure and re-integration into the social group serves certain fundamental functions for sows and piglets in natural environments; it allows sows to increase their foraging territory and feed intake during this period of increased metabolic demand for lactation. For the piglets, early adventures out of the nest site allow interaction with a diverse environment, which may have importance for nutritional and long-term behavioural development. Research on the influence of rearing in 'impoverished' conditions (i.e. barren environments such as the farrowing crate) has shown that the complexity of the nursing environment can influence subsequent cognitive abilities of pigs (de Jong *et al.*, 2000), their ability to cope with stressful situations (de Jonge *et al.*, 1996) and may influence future maternal behaviour of any female offspring (Schouten, 1987). Thus, it is possible that piglets reared in a more enriched environment are better adapted for challenges later in life, including social integration. In addition, the foraging activities displayed outside the nest site satisfy the piglets' desire to perform exploratory behaviours, rooting and manipulating substrates and beginning the adaptation to solid food intake. The early socialisation benefits the piglets by reducing the impact of weaning (Pajor *et al.*, 1999; Hessel *et al.*, 2006), particularly reducing the effects of mixing aggression. D'Eath (2005) demonstrated that pre-weaning mixing of piglets reduced aggression levels at weaning and this socialisation appeared to equip piglets with social skills that benefitted them in the long term, enabling them to more rapidly form stable dominance hierarchies during future aggressive encounters with unfamiliar pigs. Social integration at this time is also important for the sow to minimise aggressive interactions associated with re-integration that might impede her fitness. Aggression is a major problem among un-familiar pigs and can lead to severe injury and physiological stress responses which can have detrimental effects on reproductive parameters (Arey and Edwards, 1998). Such overt aggression could also risk injury to the piglets if they share this social space. Under natural or semi-natural conditions pigs maintain established groups where aggression is regulated via 'avoidance order', with specific behavioural patterns reducing risk of attacks by dominant individuals (Jensen, 2002). In studies determining the influence of recognition on aggressive interactions post-mixing (Olsson and Svendsen, 1997)

there was a clear effect of acquaintance with reduced aggression between pigs that recognised each other from their previous groups. Arey (1999) concluded that sows from the same gestational group rarely fought when mixed after 4 weeks separated in farrowing crates, thus recognition is a key factor in post-mixing aggression.

Needs-based design criteria for the nest-departure and social integration phase

Design criteria at this stage must consider the need for enrichment and social contact, and therefore the space and partition design to facilitate the latter. In addition, physical health and nutritional development for the piglet should be considered. For the former, flooring is an important factor.

Space

Space is required in order to leave the nest site. The defined space described in the previous sections to facilitate pen hygiene could accommodate the need to leave the nest site (Tables 1 and 2). Quantifying this criterion is difficult because it is more than likely that once the nest site has been left, qualitative aspects of the space are more important than actual physical area. However, in order to facilitate full social integration, additional space would be required for sows and litters to mix. The extent of this space requirement depends on how many litters and sows would be mixing, and whether the sows were familiar (i.e. came from the same social group or gestation pen). In addition to the sum of each individual's physical space requirements, space for appropriate social interaction must be considered (Baxter, 1985). If animals are unfamiliar space allocation is an important factor to accommodate the agonistic interactions associated with establishing a new hierarchy (Jensen, 1982) and facilitate escape by losers of conflicts. Amongst familiar animals, signalling of submission and avoidance of dominants also requires space (Jensen, 2002). Group size is therefore likely to be a factor influencing requirement for space per sow, with smaller total space allowances resulting in greater aggression; Jensen (1984) showed that in a group of five sows, in order for avoidance behaviours to be displayed, each sow would need 3 m² of space. In these stable groups, aggressive interactions are observed mainly in relation to competition for resources and therefore space requirements are dependent on resource accessibility (Baxter, 1985). Such resources include space for resting, feeding and excretion. However, the work carried out thus far has not included space for nursing, and whether such activity requires additional 'personal space' to that required for simply lying laterally needs additional research (Table 1). In group-housed systems, where sows and litters mix for lactation, space given (per sow and litter) varies considerably (e.g. 27 m² – Kerr *et al.*, 1988 v. 8 m² – Halverson *et al.*, 1997), with group size also varying. Baxter (1985) recommends that instead of extravagant allowances for social space, it is better to consider clever design (Table 1) allowing interaction with the ability to display submission, reduced aggression and specific activities (e.g. nursing).

The social dynamic of the group is crucial when making decisions about pre-weaning mixing and it is recommended that lactational mixing only be attempted when the sows are familiar with each other (i.e. from the same gestational group; Table 1). If this cannot be achieved, some degree of social contact can be afforded by partitions which enable visual, olfactory and even nasal contact between adjacent sows. In pre-weaned pigs, it has been shown that such 'fenceline' contact can reduce aggression at subsequent mixing (Waran and Broom, 1993) and there is anecdotal evidence of similar benefits in sows (Dellmeier and Friend, 1991). Mixing of piglets to facilitate early socialisation prior to weaning could occur without mixing of sows. By providing an additional area to that of the farrowing pen, inaccessible to the sow or providing pop-holes between farrowing pens to be opened during later lactation, unfamiliar piglets could socialise. However, although there are reported benefits (D'Eath, 2005) to pre-weaning mixing, there are also reported negative consequences, including an increase in risk of disease transmission and pre-weaning fighting with the potential to negate the post-weaning benefits (Parratt *et al.*, 2006). There are also reports of the presence of foreign litters increasing teat disputes, disrupting nursing frequency and thus reducing milk intake (Pedersen *et al.*, 1998). Thus, the costs and benefits of pre-weaning mixing make recommendations difficult. Until further definitive evidence is presented, an interim measure, which allows physical contact between neighbouring sows and their litters (e.g. through barred walls) may be beneficial in reducing the negative effects of weaning on both sows and their piglets. Such design would require no extra space, but would require different wall partitions with contact areas (Tables 1 and 2).

Enrichment

Substrate provided regularly could satisfy the need for an enriched and diverse environment. In addition, provision of substrates has been shown to decrease anti-social behaviours, including belly nosing and aggressive interactions with pen mates (Beattie *et al.*, 2000). Any form of enrichment should have properties that accommodate the motivated behaviours for the animals concerned (Van de Weerd *et al.*, 2003) which, in the case of piglets, include foraging and exploratory behaviours. Earth-like materials such as peat, mushroom compost (Beattie *et al.*, 1998) and more complex materials such as branches (Pedersen *et al.*, 2005) have been shown to be preferred as enrichment substrates over straw (Table 2). The amount of substrate necessary to fulfil this enrichment function in young piglets has not, to our knowledge, been quantified. Most enrichment experiments indicate that it is the novel aspect of the enrichment that stimulates exploratory behaviour. In piglets aged between 4 and 8 weeks, Fraser (1985) observed two main peaks in activity that coincided with delivery of fresh straw. These piglets were provided with either 1 or 2.5 kg of fresh straw twice daily in two experimental groups, with activity levels not significantly different. Research in older pigs also suggests that relatively small quantities of straw, if presented

daily, appear to be almost as effective at generating greater straw-directed behaviour and less pig-directed and pen-directed behaviour as large amounts (Kelly *et al.*, 2000). However, Day *et al.* (2002) found that an increasing provision of straw resulted in an increase in the proportional frequency of rooting and ploughing behaviours and an associated decrease in potentially damaging pig-behaviours, such as tail-biting. Further research is needed to determine the quantities of substrate needed to provide pre-weaned piglets with an enriched and diverse environment. Although substrate is likely to encourage foraging behaviours, at this stage, food that aids nutritional development (i.e. creep feed) should also be provided (see later section on nutritional development and weaning; Table 2).

Flooring

If the enrichment provided is to be straw (despite its less preferable rooting and foraging properties than some other substrates) then it is possible that, as substrate is required to fulfil other functions such as physical and thermal comfort, the quantity can first be defined with these needs in mind. The amount of straw needed for thermal comfort will depend on other properties of the environment. Fraser (1985) showed a distinct preference in weaned piglets for bedded areas when the ambient temperature was between 18°C to 21°C and not at 25°C to 27°C. When thermal comfort was not compromised there was no clear preference for lying on bedded or concrete areas. These results suggest that thermal comfort is of greater importance than physical comfort in young pigs. Straw bedding can reduce the prevalence of skin lesions and bursae in older pigs (Moultotou *et al.*, 1999) but pressure from hard flooring is likely to cause less discomfort in younger, lighter piglets. However, hard flooring could cause discomfort and injury for young piglets when they make contact with the floor during the vigorous activity of suckling. Moultotou and Green (1999) found a positive correlation between time spent suckling and incidence of carpal skin abrasions between 4 and 6 days of age. Thus deep straw bedding, at least during the 1st week of life, could have protective benefits for younger piglets (Table 2). In order for this recommendation to be fulfilled, the flooring where the straw is provided needs to be solid to prevent the straw falling through the slats (Tables 1 and 2). It is clear from the literature that the amount of bedding required for physical comfort is poorly defined, especially in relation to the age and weight of pigs, and therefore such quantification requires additional research.

Properties of the floor, such as slip-resistance, abrasiveness, surface profile, hardness, void width (slatted floors) and thermal resistance (already discussed) are important factors that contribute to its injury potential. As with thermal comfort, physical comfort requires balancing sow and piglet needs. For example, slip-resistance, particularly for the sow, needs to be achieved without modifying the floor's characteristics in such a way that predisposes injury through excessive abrasion (McKee and Dumelow, 1995). Abrasion is a common risk for suckling piglets, with mixed reports as to

which flooring material causes the highest incidence of knee damage: Furniss *et al.* (1986) found that the worst knee damage was seen on an old cement screed. In contrast, Clark (1985) found that newly installed concrete screed had the highest abrasive properties, whereas the same floor after 3 months continuous use had the lowest abrasiveness. Therefore, both floor material and its deterioration over time require consideration; repairing solid flooring and using specialised screed offering both grip and low abrasion properties has shown to decrease piglet injuries (Zoric *et al.*, 2009). Any flooring needs to demonstrate these two properties (Tables 1 and 2); straw-bedding (Vellenga *et al.*, 1983; Edwards and Lightfoot, 1986) or solid flooring covered with peat (Zoric *et al.*, 2008) offer the lowest risk of injury. However, hygiene is an important consideration and slatted floors assist with hygiene (Rantzer and Svendsen, 2001), as well as thermal comfort for the sow during lactation in warm conditions. Incorrectly designed slatted flooring can cause injuries to piglet feet (particularly the coronet and footpads, Lewis *et al.*, 2005), as well as damage to sow teats and legs (Edwards and Lightfoot, 1986). If slatted floors are to be used (e.g. in the dunging area), the recommended void width is no greater than 10 mm with rounded edges (Mitchell and Smith, 1978; see Table 2), and plastic-coated metal has been shown to be less injurious than steel (Furniss *et al.*, 1986; Lewis *et al.*, 2005). In addition, void width with respect to use of straw or other substrate that may cause clogging needs to be considered. Many new plastic types of flooring are now available and widely used, but few have been scientifically assessed.

Thus far, the basic needs such as food and water for the sow have been ignored presuming these are already well catered for as fundamental physiological requirements. However, it is important to emphasise that the sow must increase her feed and water intake during this time to accommodate the significant metabolic demands of lactation. Certain aspects of the environment can hamper this, such as increased environmental temperatures (Black *et al.*, 1993), as well as restrictive conditions. It has been reported that sows kept in loose-housed environments have a higher intake of food during lactation than animals kept in farrowing crates (Pajor, 1998). It is known that there is a correlation between food intake and heat stress. Recent work has showed that localised cooling of the sow's shoulders while in the farrowing crate increased sow's feed intake and consequently piglet weight gain (Silva *et al.*, 2006; van Wagenberg *et al.*, 2006). Designing an environment with temperature differentials could facilitate thermal comfort, as well as encourage the animals to use the defined spaces for the functions they are intended for (Table 1).

Nutritional development and weaning

Sow and piglet behaviour and physiology

Studying pigs under semi-natural conditions, Jensen and Recén (1989) observed weaning to occur at 17.2 weeks of age. Prior to weaning, there was gradual separation

between the sow and her litter, with progressive changes in suckling behaviour also evident. For example, sows became less permissive of suckling until, after 4 weeks, sows would terminate 100% of sucklings. This has also been demonstrated in experimental indoor systems in get-away pens (GAPs – Bøe, 1991). In this system, where sows could leave the piglets voluntarily without the piglets being able to follow, suckling frequency decreased gradually from 22.9 to 4.3 bouts every 24 h over a 10-week period. During this experiment, average weaning age was between 11 and 12 weeks and half of the sows were observed to wean their piglets before the piglets were 10 weeks of age (Bøe, 1991). The discrepancy between these weaning ages and those observed by Jensen and Recén (1989), suggests that many sows would wean earlier if given sole responsibility, yet piglets continue to solicit milk for a much greater period of time if allowed to follow the sow. However, under more natural conditions, it is unlikely that the sow would ever be able to totally leave her litter without, at least, the fittest piglets being able to follow. It could therefore be argued that the expectation that the piglets will follow her is part of the innate behaviour of the sow and that results from experiments using GAPs (Bøe, 1991) are inconclusive regarding motivation to wean earlier than reported 'naturally'. Regardless of this, conflict is evident: the sow needs an environment that allows time away from the piglets to gradually decrease milk let-downs and promote the weaning process. In contrast, the piglets need an environment where they can follow the sow to prevent litter desertion and prolong the suckling period to allow gradual transition to solid food.

In natural or semi-natural environments, the piglets' dependency on the sow's milk for nutrition gradually decreases. Piglets have been observed to display foraging behaviours as early as the first few days *post partum* (Petersen, 1994) and after 4 weeks old they gradually increase their time spent foraging. Thus, they can survive without milk at this time provided that alternative food resources are available. This is related to season, with weaning being observed to be later when piglets were born between July and October, with expected weaning during the winter months (Jensen and Recén, 1989).

Functional importance of behaviours during this phase

During the latter stages of lactation, the needs of the sow and her litter become increasingly dichotomised as a power struggle over maternal resources develops because of conflicting evolutionary strategies (Trivers, 1974). The piglets must consider their own survival and soliciting as much milk as possible from the sow will aid in their growth and development. The strategy adopted by the sow is one of balance: she must balance the needs of her current litter with the potential for any future litters, and thus her overall reproductive success. Therefore, in order to maintain body condition while still providing for her current litter, she will reduce the number of milk let-downs per day. This can only be efficiently accomplished by a gradual separation from the litter, thus a control of her lactational output and progressive weaning. Abrupt weaning under more intensive conditions

causes nutritional challenges for the young, can slow growth rate and compromise immune function (Algers, 1984; Pajor *et al.*, 1999). Within 24 h of weaning, there are marked changes in the structure and function of the small intestine resulting from temporary reduction in feed intake (Pluske *et al.*, 1995), with consequential growth check and frequent incidences of diarrhoea. Recently, attention has also been drawn to the possible psychological and long-term consequences of early weaning (Newberry and Swanson, 2008; Weary *et al.*, 2008). Prior to weaning, piglets will be used to regular and synchronised feeding patterns, at this stage controlled by the sow delivering a highly nutritious and palatable milk source (Pluske *et al.*, 1995). Abrupt weaning involves a complete change in the pattern and delivery of food, requiring both behavioural and physiological adaptations by the piglet. If supplementary food is available from at least the 3rd week of lactation, when milk production starts to decline, expression of foraging behaviour has functional consequences for changes in gastric enzyme secretions and gut development (Cranwell, 1995), allowing the piglet to experience a more gradual weaning process. It is possible that, if these foraging needs are met, then the piglet will take a more active role in weaning; Jensen and Recén (1989) proposed the 'fast-food' hypothesis whereby a cost-benefit scenario occurs in which the cost of 'asking' the sow for milk is gradually outweighed by the benefits of foraging for food.

Needs-based design criteria for the nutritional development and weaning phase

From the evidence presented above, the needs of the piglets and sow during this time will be difficult to balance given the trade-offs and parent-offspring conflict described. Assuming the nutritional needs of the sow are met, the design must consider suitable space and flooring to facilitate sow controlled nursing and physical and thermal comfort, respectively. To meet piglet needs, suitable substrate and feed should be provided to promote foraging and encourage nutritional independence. Approaches to ease the transition to weaning should consider minimising both physiological and psychological stressors. A recent review by Weary *et al.* (2008) summarised these approaches as: increasing weaning age, increasing the time the dam and her young spend apart before weaning and making the solid diet more attractive to the pre-weaned young. With respect to the design criteria, the latter two approaches, in particular, require recommendations on how best to accommodate them.

Space

Designing the space required during this time involves a question of balance; the sow needs space to 'escape' her piglets to control lactational output, but the piglets need to avoid total desertion. In GAPs, where the sow could access the feeding and dunging area without the piglets, sows lost less weight and returned to oestrus quicker than sows in confined systems and piglets gained weight and switched to solid food quicker than piglets in confined systems (Pajor, 1998). It has also been shown that in a farrowing environment

which allows 'escape' by the sow, more 'sow-controlled' nursing behaviour developed, which was considered an important aspect of good mothering ability (Thodberg *et al.*, 2002). Though benefits of systems where the sow can leave her piglets freely are evident, there are potential risks of the nursing frequency decreasing to a detrimental level for the piglets or complete abandonment (Bøe, 1993). Environments which encourage voluntary gradual separation are recommended (Weary *et al.*, 2008). Quantifying the space needed to accommodate gradual separation is difficult and, as already mentioned in previous sections, qualitative aspects of the space maybe more important than its actual physical size. Providing defined areas (Table 1), gives the sow options to move away from her piglets. Potentially making certain areas less attractive to the piglets, yet still accessible, would encourage gradual separation; for example, temperature differentials between the defined areas and/or different flooring, enrichment and food provision (Table 1).

Nutritional provision

Design criteria in the previous section to promote social integration and development via appropriate space and substrate will reduce the physical and psychological consequences of early weaning (Newberry and Swanson, 2008) (Tables 1 and 2). In addition, suitable substrate and supplementary feed will encourage foraging behaviours to reduce the impact of nutritional challenges and promote weaning decisions in piglets. It is generally accepted that higher intake of solid feed (or creep feed) prior to weaning results in higher intake post-weaning (Aherne *et al.*, 1982). However, individual differences in pre-weaning creep feed intake are evident; Barnett *et al.* (1989) found total creep feed consumption varied from 13 to 194 g/piglet and from 107 to 1550 g/litter. In addition, some piglets do not eat solid feed at all prior to weaning; using a faecal dyeing technique Callesen *et al.* (2007) identified 78% of piglets as 'eaters' and 22% as 'non-eaters'. Individual piglets appear to vary in their feeding strategies, with some electing to continue suckling and engaging in energy consuming teat stimulation and others prepared to start feeding on solids sooner (Bøe and Jensen, 1995). Since the former strategy results in a more detrimental impact at weaning, encouraging all piglets to sample solid feed prior to weaning should be a design objective in any farrowing system. Appropriate delivery of this supplementary feed to ensure piglet accessibility (Table 2) may influence the success of nutritional development (Appleby *et al.*, 1991 and 1992). Trough designs which increase available feed space and the chance for social facilitation appear to promote feed intake; shallow feeders, rather than traditional hoppers, (Wattanukul *et al.*, 2005) and Playfeeders (Kuller *et al.*, 2010) which stimulate exploratory behaviours have proved most successful (Table 2).

Pre-weaning water intake is an over-looked area, and low feed intake is often compounded with low water intake (Dybkjaer *et al.*, 2006). As with food intake, similar approaches to increasing the attractiveness of water dispensers could influence consumption rates. Larger water dispensers

(e.g. circular bowls) facilitate social drinking and accommodate the development of synchronous behaviour observed in social animals (Phillips and Fraser, 1991). However, in loose-housed environments a water bowl maybe disturbed by the sow and bowls can result in hygiene issues if fouled. After trialling different designs, Phillips and Fraser (2001) showed success via speed of discovery and use with an upward angled bite nipple drinker placed close to the floor (Table 2).

Conclusions

This review has documented the considerable amount of literature describing the biological needs of the sow and her piglets during the different phases of farrowing and lactation. It has highlighted the evolutionary significance, and thus function, of certain behavioural patterns that continue to be displayed under farmed conditions. Identifying and summarising suitable design criteria to accommodate biological needs has highlighted that, despite the abundance of work in this area, there remain out-standing issues requiring additional and detailed research. Quantifying space and substrate need at specific stages, as well as the potential benefits of a quiet nest site are examples of such issues. It is evident that there are a number of trade-offs in operation throughout the phases of farrowing, not only between different animals but also between different goals of the individual, complicating the ability to design a suitable farrowing and lactation environment that meets all biological needs. Though not a focus of this review, further complications will exist when considering the farmer's interests and a successful system should attempt to reconcile the 'triangle of needs' between sow, farmer and piglets, to maximise productivity and welfare.

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