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Animal welfare and economic optimisation of farrowing systems

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Abstract

In many countries, including the UK, the majority of domestic sows are housed in farrowing crates during the farrowing and lactation periods. Such systems raise welfare problems due to the close confinement of the sow. Despite the fact that many alternative housing systems have been developed, no commercially viable/feasible option has emerged for large scale units. Current scientific and practical knowledge of farrowing systems were reviewed in this study to identify alternative systems, their welfare and production potential. The aim was to establish acceptable trade-offs between profit and welfare within alternative farrowing systems. Linear programming (LP) was used to examine possible trade-offs and to support the design of welfare-friendly yet commercially viable alternatives. The objective of the LP was to optimise the economic performance of conventional crates, simple pens and designed pens subject to both managerial and animal welfare constraints. Quantitative values for constraints were derived from the literature. The potential effects of each welfare component on productivity were assessed by a group of animal welfare scientists and used in the model. The modelled welfare components (inputs) were extra space, substrate and temperature. Results showed that, when using piglet survival rate in the LP based on data drawn from the literature and incorporating costs of extra inputs in the model, the crates obtained the highest annual net margin and the designed pens and the pens were in second and third place, respectively. The designed pens and the pens were able to improve their annual net margin once alternative reference points, following expert-derived production functions, were used to adjust piglet survival rates in response to extra space, extra substrate and modified pen heating. The non-crate systems then provided higher welfare and higher net margin for sows and piglets than crates, implying the possibility of a win-win situation.

Keywords: *alternative housing systems, animal welfare, economic optimisation, farrowing systems, linear programming, pig*

Introduction

Farm animal housing systems have implications for animal welfare and health as well as for economic and technical performance. Intensive livestock production, with particular emphasis on high productivity and profit, imposes restrictive and in some instances controversial, if not unacceptable, housing conditions for production animals (Fraser 2008). Sow farrowing crates are an example of such systems, which continue to be a focus for public concern and debate. In 2008, approximately 427,000 sows and gilts were held in 6,100 breeding holdings across the UK (82% in England, 9% in Scotland and 9% in Northern Ireland) (BPEX 2009). The majority of UK indoor sows are farrowed in crates; despite a growing outdoor sector — it was reported that around 73% of all breeding sows farrowed in crates in 2006 (Defra 2007).

The major concerns about farrowing crates are related to the welfare of the sow, as her movement is highly restricted and natural nest-building behaviour severely suppressed within these systems (Lawrence *et al* 1994; Jarvis *et al* 1997; Damm *et al* 2002; Wischner *et al* 2009). Development of an alternative economical farrowing system that promotes high welfare for sows and piglets has been identified as beneficial for industry and the animals (Johnson & Marchant-Forde 2009). However, such an alternative system still requires further development to harmonise with large scale commercial production (Edwards & Fraser 1997). An ideal alternative system would maximise piglet survival, allow sows to perform their natural patterns of behaviour, reduce labour and provide a good working environment and incur lower capital requirements compared with conventional systems.

Although many alternative housing systems have been developed in different countries, no commercially viable and feasible indoor option has emerged for large scale units. Cain and Guy (2006), who analysed the costs of producing weaner pigs under a range of housing systems with different levels of welfare for the sow, reported that pig production costs tend to be higher in systems which are judged to

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provide better conditions for the sows' welfare. They concluded that part of the higher cost of constructing and managing these higher welfare systems may be offset by better animal performance. However, the main conflict yet to be resolved is between the sows' reproductive performance (profit) and sow and piglet welfare. This conflict is largely an issue of how to provide the appropriate level of environmental enrichment to meet the biological requirements of the farrowing sow, given management and business constraints. Another challenging issue relates to the assessment of relationships between different components of the systems and better animal performance. To tackle these, a combination of economics and science has been suggested to design housing systems that provide high levels of animal welfare in ways that address animal needs at least cost, and thus maximise potential for uptake in commercial agriculture (Stott & Lawrence 2009). This can be achieved by developing bio-economic models, which provide useful frameworks to analyse alternative systems and support new designs.

Work by Newcastle University and SAC for the UK government, under the project entitled: 'Re-designing the farrowing environment from first principles to optimise animal welfare and economic performance', aims to: i) identify and investigate alternative indoor free farrowing systems which are commercially viable, and ii) develop and redesign the farrowing environment from biological first principles to maximise welfare and production performance of piglets and sows. In this context, animal welfare scientists, engineers, expert stakeholder groups and economists worked together to synthesise information to identify a system prototype including potential innovations. An optimisation approach, presented in this paper, was used as part of the design process to test possible trade-offs between profit and welfare within alternative indoor farrowing systems. Three systems, including conventional crates, simple pens and designed pens (ie pens modified with separation of dunging and lying areas and addition of pen 'furniture') were studied to explore the possibility of providing higher welfare within the context of commercially viable alternatives to farrowing crates. The main objective of this paper is to outline the optimisation framework used as part of the design process, highlighting the main issues arising at the biological-economic interface and the first steps taken to address them.

Materials and methods

Definition of farrowing systems

From the available scientific literature on alternative farrowing environments, systems were classified and descriptions are based on averaging the data available. Such a technique involves caveats regarding both quantity and quality of the data available; given that some information, particularly for the farrowing crates, was obtained from dated literature. Expert opinion and current knowledge were sought to determine if the definition of systems was sensible and the descriptions refined for the optimisation model. The following descriptions defined the systems.

Farrowing crate (CRATE)

The crate description is based on 86 studies using farrowing crates. Tubular metal bars run longitudinally along the farrowing pen, with a feeder and drinker at one end and a removable barrier at the rear, adjustable for length of sow. The sow is restricted within this frame with, on average, 1.26 m^2 of floor space available. The crate is fixed within a pen area of 3.54 m^2, with low solid-sided walls to keep piglets within the home pen. Typically, fully slatted floors occupy 75% of the floor space and sit above a slurry system for ease of manure removal and pen hygiene. The remaining 25% is solid flooring for the piglets (typically plastic) with a heat lamp or heat mat providing localised heat (30°C). The ambient temperature of a farrowing house averages 21.2°C. Substrate (eg straw) is rarely provided.

Pen

The pen description is based on 62 studies using different types of basic farrowing pen. On average, farrowing pens occupied 10.48 m^2 of space with solid flooring (typically insulated concrete). Walls were typically solid-sided. The pen is a uniform space with no definition between excretory and lying areas. Piglets are provided with a separate 'creep' area with supplementary heat via a lamp or mat. There is no other piglet protection in the pen. Ambient temperature of the farrowing house averages 20.1°C. Substrate is provided, with, on average, 2.7 kg of straw supplied.

Designed pen

The designed pen is based on 20 studies using different types of 'designed pens', including the Schmid (Schmid 1993), Werribee (Cronin *et al* 2000) and FAT pens (Weber 2000). The designed pen typically has separate excretory and lying areas. The whole pen occupies, on average, 7.06 m^2 of floor space, with the area designated for nesting/lying occupying approximately 2.90 m^2 of this space. Flooring in the nest area is solid (typically insulated concrete) and either slatted in the excretory area (typically plastic-coated metal) or solid. Walls are solid-sided with at least one wall having either a farrowing rail or sloped wall for piglet protection. Piglets are provided with a separate 'creep' area with supplementary heat via a lamp or mat. Ambient temperature of the farrowing house typically averages 20.5°C. Substrate is provided with, on average, 3.1 kg of straw supplied.

Data

Quantitative values from 145 items of the reviewed literature were used to populate a database providing required data on the studied farrowing systems to be used in the optimisation model (Table 1) (an ongoing SAC project). Total mortality was used as a production result from the literature to ensure that both live-born and still-born mortalities, which are sometimes mis-classified, were taken into account. SAC (2009) was used as the main source of other economic performance data for the studied systems (Table 2).

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Table 1 Mean (± SEM)[a] input parameters derived from 145 studies of the reviewed literature used in the LP.

Input parameters	Crates	Pens	Designed pens
Sample size[b]	713 (± 629)	862 (± 814)	559 (± 507)
Litter size (fixed as constant)	11	11	11
Total piglet mortality (%)[c]	18.18 (± 1.3)	18.42 (± 2.7)	16.54 (± 1.2)
Space (m^2 per sow and piglets)	3.54 (± 0.12)[d]	10.48 (± 1.05)	7.06 (± 0.25)
Substrate (kg per litter)	0.22 (± 0.25)	2.68 (± 0.64)	3.14 (± 0.49)
Labour (h per sow per year)	6.74 (± 4.13)	12.76 (± 0.02)	8.45 (± 8.47)
Ambient temperature (°C)	21.26 (± 0.46)	20.20 (± 0.67)	20.09 (± 1.75)
Investment (£ per sow place)[e]	1,843	1,988	2,165

[a] Values in brackets represent standard errors (SEM) adapted from an ongoing SAC project.
[b] Average number of sows used in the trials.
[c] Including live-born and stillborn mortality.
[d] Available floor space for the sow in the farrowing crate is 1.26 m^2.
[e] Based on a manufacturer estimation (G Baker, Quality Equipment Ltd, personal communication 2009). Equivalents in € per sow place were 2,088, 2,252 and 2,452 for crates, pens and designed pens, respectively (assuming an exchange rate of €1.13 to £).

Table 2 Input costs and output prices used in the LP.

Resource	Unit	Physical input	Cost or price per unit £ (€)[a]	Reference
Weaner value at age 28 days[b]	Pig		39 (44)	Authors' estimation
Power required for sow	kwh per sow per year	7	0.14 (0.16)	Carbon Trust (2005)
Power required for piglet	kwh per piglet per year	8	0.14 (0.16)	Carbon Trust (2005)
Labour of average skill	h		7.5 (8.5)	AWB (2009)
Bedding (straw)	kg per sow		0.05 (0.06)	SAC (2009)
Sow feed	kg per sow per annum	1,459	0.24 (0.27)	SAC (2009)
Creep feed	kg per sow per annum	63	0.72 (0.82)	SAC (2009)
Veterinary input	Per sow per annum		24 (27)	SAC (2009)
Other livestock expenses[c]	Per sow per annum		53 (60)	SAC (2009)

[a] Values presented in Sterling and Euro currencies (figures between the brackets), assuming an exchange rate of €1.13 to £.
[b] Weaners are sold at £55.00 at 80 days of age (SAC 2009). Weaner value at an age of 28 days is estimated as: £55.00–£16.00 (variable costs of growth after 28 days) = £39.00.
[c] Other livestock expenses include miscellaneous items, such as transportation costs, disinfectants, etc.

Welfare score assessment

In parallel to the optimisation exercise, a welfare score for each system was developed using a methodology devised in this project and based on identifying the biological needs of the sows and piglets during the three main phases of farrowing; nest-building, parturition and lactation (Baxter *et al* in press). The needs were compiled by reviewing data on the 'natural' behaviour of sows and piglets and further enhanced by accounting for needs, particularly of piglets, of animals housed under indoor and more intensive conditions (an ongoing SAC project). The score was assigned by 'asking' each system a set of over 50 questions based on these biological needs of both sows and piglets during the different phases described. A positive response to each question was always considered positive for welfare and the score was developed based on the ratio of positive to negative responses. The score was weighted to account for the litter, so that questions relating to piglet welfare were multiplied by average litter size of 11. The questions to develop a welfare score were based predominantly on scientific evidence. Where this evidence was lacking, certain assumptions were made based on expert opinion and biological argument. An example of this occurred when asking questions about space; the welfare of the sow is increased when moving from a restricted space (ie a farrowing crate), where she is unable to turn around, to a more open space where she can turn around. Scientific evidence regarding the stress physiology under these different situations, shows elevated cortisol under restricted conditions (Lawrence *et al* 1994; Jarvis *et al* 1997), supporting this statement. Furthermore, it can be stated that sow welfare is increased when she is given space to increase her activity and accommodate seeking behaviour during nest-building (Jensen 1986). When reviewing biological

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needs (Baxter *et al* in press), it was determined that a minimum of approximately 5 m^2 would facilitate this. However, for larger space arrangements, there are no data to our knowledge that support the statement that the welfare of the sow is increased if, for example, she has 10 m^2 space to use. However, we assume from observations of sows under natural or semi-natural conditions (Jensen 1986) that for the nest-building phase she would prefer a larger space and therefore positive responses are awarded if the system provides this at the stage when the sow needs it.

Optimisation model

The objectives were achieved by developing and running a linear programme (LP) (Luenburger & Ye 2008; Williams 2008). Linear programming is a mathematical technique for optimising an outcome in a given system (eg maximising profit or minimising cost) subject to linear equality and linear inequality constraints of the system. It normally consists of an objective function (eg profit) to be maximised or minimised, a set of activities (eg keeping sows, producing piglets, etc) and a set of constraints, which specify a so-called 'feasible area' over which the objective function is to be optimised. Linear programmes can be expressed in mathematical form (Hazell & Norton 1986):

Maximise $(Z = c'x)$

Subject to $Ax \leq b$

And $x \geq 0$

where Z is the net margin to be maximised, c' denotes the vector of margins or costs per unit of activity (eg costs per sow not accounted for in another activity), x denotes the vector of activities (eg sows), A represents the matrix of technical coefficients to link activities with resources/constraints (eg space per sow) and b gives the extent of the technical or physical constraints/resources (eg total space available in a building).

LP was used to establish the profit (measured as net margin) maximising farm management strategy for a given farrowing system subject to constraints that reflect the main resource limitations and aspects of the welfare of the sow and piglet. The LP was implemented in Excel® (Microsoft Corporation 2002) and the Excel Solver® add-in tool was used to run the model.

The LP uses technical coefficients to link key activities with resources they require, such as feed, labour, space, substrate, power and capital investment. This provides the physical input-output relationships determining profitability. The LP then chooses the combination of activities that maximise the objective (ie net margin at age 28 days coming from sales of weaners minus attributed fixed and variable costs) subject to the resource constraints applied. However, in this case, the welfare implications of the system chosen also needed to be incorporated.

Biological needs of the sow and piglets during nest-building, parturition and lactation phases were therefore reviewed (Baxter *et al* in press) and three main 'welfare components' (WC) namely space, substrate and temperature (ie the cost of electricity required to generate sufficient ambient temperature to meet the welfare needs of sow and piglets) were identified for use in this model. Their contribution to optimum welfare of both sow and piglet was the main rationale for selecting these components. Space allows free movement of the sow and expression of nest-building behaviour. Substrate facilitates expression of nest-building behaviour, reduces pig mortality due to crushing and enhances microclimate. Maintaining proper ambient temperature is crucial for optimum sow function and piglet survival.

WCs were considered as limited resources and therefore restrictions on their maximum usage were introduced to the LP depending on the system being modelled. At the default, these constraints were set as the average total usage of WC resources derived from the literature (checked and refined by experts where appropriate) (Table 1). Also in Table 1 are literature-derived estimates of labour requirements and total piglet mortality. A fixed initial litter size was used across all systems (ie system was assumed to have no effect on litter size). Investment costs in Table 1 were obtained by expert assessment (Glyn Baker, Quality Equipment Ltd, personal communication 2009). Investment costs per sow place for different housing systems included costs of materials, design and labour for manufacturing the basic internal structures. The costs of accessories and furniture, such as flooring materials, creep areas, bars, gates, walls, drinkers, feeders, etc were also included in total investment costs for every system. It was assumed that that the shell of the building was in place, which includes plumbing, electricity and ventilation.

Keeping sows, producing litters and weaners, providing certain levels of feed, labour, space, substrate, electricity (for heating) and investment were the main activities in the model. Technical coefficients for production activities dealt with litter size and piglet mortality, thus providing number of piglets at a standard weaning age to give piglet-to-weaner flow. To account for sow and piglet welfare, additional activities, including providing extra space, extra power and extra substrate were introduced to allow these WC constraints to be varied from the default within constraints set by the system if this generated a higher net margin. If selected by the model, this extra provision may improve welfare and possibly productivity (ie reduced piglet mortality) at some additional expense (Table 2).

Constraints were imposed to limit the maximum reductions in piglet mortality that could be achieved using extra WC within each housing system, to take account of the probable lack of additivity of mortality reduction attributable to different WC at the extremes. These were based on the mean mortalities derived from the literature, less 1.96 standard errors from these means (lower 95% confidence limit), thus representing a range based on a measure of the variation in reported average mortalities. Means and standard errors used are shown in Table 1. The minimum total piglet mortalities calculated in this way were 15.63, 13.07 and 14.17% for the crates, the pens and the designed pens, respectively, as a result of using extra WC.

The costs of space were implicitly included in the investment costs. As increasing sow space is impossible in the crate systems, assigning no additional expense to margin-

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Figure 1

Diagrammatic representation of the linear programming input/output relationships.

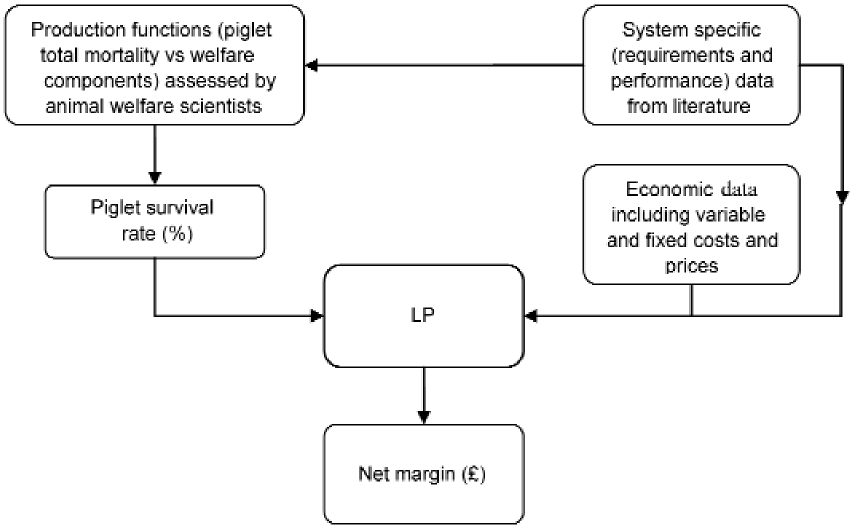
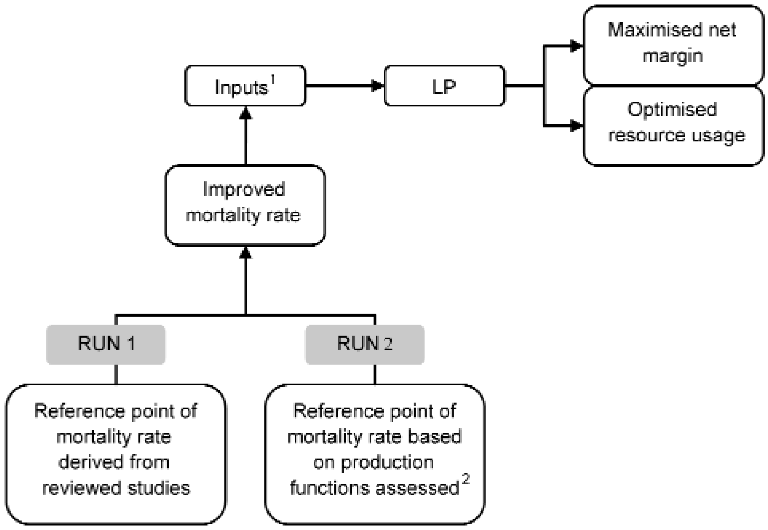


Figure 2

Diagrammatic representation of the LP runs performed. [1] Including constraints on welfare components, keeping sows and the production of piglets and weaners. [2] Relationships presented in equations 1–3.



ally increased space gave the pens and the designed pens an unrealistic advantage in the LP. To address this problem, the cost price of extra space for the pens and the designed pens was estimated at £1.46 per m^2 and £2.37 per m^2 per sow cycle, respectively, based on the required investment costs (Table 2), the number of annual cycles per sow place (10.4) and expected building lifetime of 20 years. These figures were used as the prices of buying extra space by the LP for the pens and the designed pens.

Productivity improvement due to extra WCs was incorporated in the LP by introducing extra coefficients representing an assessed link between extra WCs and extra piglet survival based on expert-derived polynomial equations explained in the next section (Figures 1 and 2). In total, three extra coefficients (one for each WC) were used in the LP. These extra coefficients were calculated from the difference between the predicted piglet mortality, derived from the prediction equations, for the extra WCs in use, and a reference-point mortality representing the level of mortality expected in the absence of extra WCs. The reference-point mortality could be derived from the prediction equations themselves, derived from the literature on system performance or set to alternative values. The LP would then enhance welfare by including extra WCs up to a maximum constraint within each system provided that the extra WCs raised net margin. The cost or benefit of additional welfare beyond the constraints could be estimated using sensitivity analysis. This was performed by conducting a series of alternative

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runs to evaluate the sensitivity of the results (ie net margins) to some of the assumptions used to vary impacts and levels of extra WCs. The alternative runs were obtained by adjusting the assumed reference-point mortality for each system. In addition, the sensitivity of the designed pen net margin predictions to alternative baseline levels of space and substrate were tested. Figure 1 provides a diagrammatic representation of the LP's input-output relationships.

Production functions

As a first attempt at determining the relationships (production functions; Debertin 1986) between outputs (total piglet survival) and inputs (WCs) needed to parameterise the LP, animal welfare scientists provided representative data based on available scientific evidence rather than expert opinion. Assessment of these relationships is, however, limited by the scarcity of relevant underlying data, thus introducing a degree of uncertainty about them and the model's outputs. Equations 1–3 present polynomial curves fitted to the assessed production functions for the three WCs space, substrate and temperature:

$$Y_{sp} = 0.0595x_i^2 - 1.6667x_i + 21.429 \quad (1)$$

$$Y_{su} = 0.0004x_i^3 + 0.0382x_i^2 - 0.8703x_i + 17.39 \quad (2)$$

$$Y_{te} = 0.2309x_i^2 - 9.0927x_i + 106.28 \quad (3)$$

Where Y_{sp}, Y_{su} and Y_{te} denote total mortality rates in percentages predicted for space, substrate and temperature, respectively, and x_i denotes quantities of WCs provided in a given system at which the mortality rates were determined.

The assessed relationships, within the working ranges, between total piglet mortality rate and quantity of substrate and temperature were both U-shaped. Available evidence suggests that providing extra substrate above 2 kg per sow reduced total piglet mortality rate because of positive effects on maternal behaviour as a result of nest-building expression (Damm *et al* 2003; Pedersen *et al* 2003; Baxter *et al* in press), improved thermal balance of newborn piglets (Mount 1967) and cushioning properties if crushing events occurred (Baxter *et al* 2009). However, excessive substrate may lead to increased mortality due to impaired piglet mobility. Mortality increases with reduction in farrowing room temperature below 18ºC because of increased piglet hypothermia (Herpin *et al* 2002) and increases above 21ºC because of adverse effects on sow feed intake and milk yield (Black *et al* 1993).

Equations 1–3 were used to establish extra coefficients used in the LP to improve mortality rates of the three studied systems. The reference points chosen were 21.43, 23.45 and 16.76 for Y_{sp}, Y_{su} and Y_{te}, respectively. For space and substrate these reference points reflect assumed maximum levels of total mortality (worst case scenario) derived from equations 1 and 2. In the case of temperature, the reference point is for minimum total mortality reflecting the sensitivity of this WC to deviations from this point in either direction. In the case of crates where no extra substrate is given, the high reference point for substrate implies a benefit of no extra substrate (23.45–17.369, see equation 2). However, as the LP constraint on extra substrate in crates was set to zero this benefit was not applied. For pens and designed pens, the baseline level of substrate implies an applied benefit down to the minimum mortality rate constraints set as described.

LP runs

Two main runs of the LP were undertaken for each of the three studied farrowing systems to optimise them under two different scenarios. In the first run, the optimum (maximised net margin) management of the systems was established with reference points on piglet mortality rates based on baseline assumptions drawn from the literature (RUN1). The second run optimised the systems based on reference points for piglet mortality rates derived from the production functions assessed by welfare scientists as described above (RUN2). Also, in RUN2, the constraints on improvements in the total piglet mortality rates were relaxed allowing the LP to utilise extra WCs if profitable. In both RUN1 and RUN2 the costs of extra inputs (including space) were used in the LP to generate the results. Figure 2 provides an overview of the LP runs performed.

In addition, the break-even costs of extra building space needed to make the net margin of the pens and the designed pens equal to the net margin of the crates were estimated in RUN2. These break-even costs of extra space were then compared with experts' building cost estimations to assess the net cost or benefit of extra space provision.

Further runs were conducted for the sensitivity analysis of the effect of changing the reference-point mortality rates and various amounts of substrate on the net margins of the systems assuming no cost for extra space.

Results

Economic performance and welfare scores

In RUN1, the crates obtained the highest annual net margin (for production of weaners at 28 days) per sow (£203.00). The designed pens and the pens with net margins of £191.00 and £175.00 were in second and third place, respectively (Figure 3).

In RUN2, the designed pens and the pens showed an increase of about 17 and 19%, respectively, in annual net margin (giving net margins of £223.00 and £209.00, respectively) compared with RUN1. The annual net margin of the crates deteriorated by 10% in RUN2 (£183.00).

In RUN2, the break-even costs of extra building space needed to make the net margin of the pens and the designed pens equal to the net margin of the crates were £3.10 and £7.50 per square metre, respectively, compared to calculated real costs of £1.50 and £2.40, respectively (see *Materials and methods*). In other words, to break even with crates, extra space could be significantly more expensive than it was assumed to be in RUN2 for both the pens and the designed pens. The capacity to carry higher costs for extra space was much greater in the designed pens than in the pens.

Taking account of sow and piglet needs, the designed pens obtained the highest welfare score of 2.39 whereas the crates achieved a score of 1.29 which was slightly higher than the pens' welfare score of 1.02.

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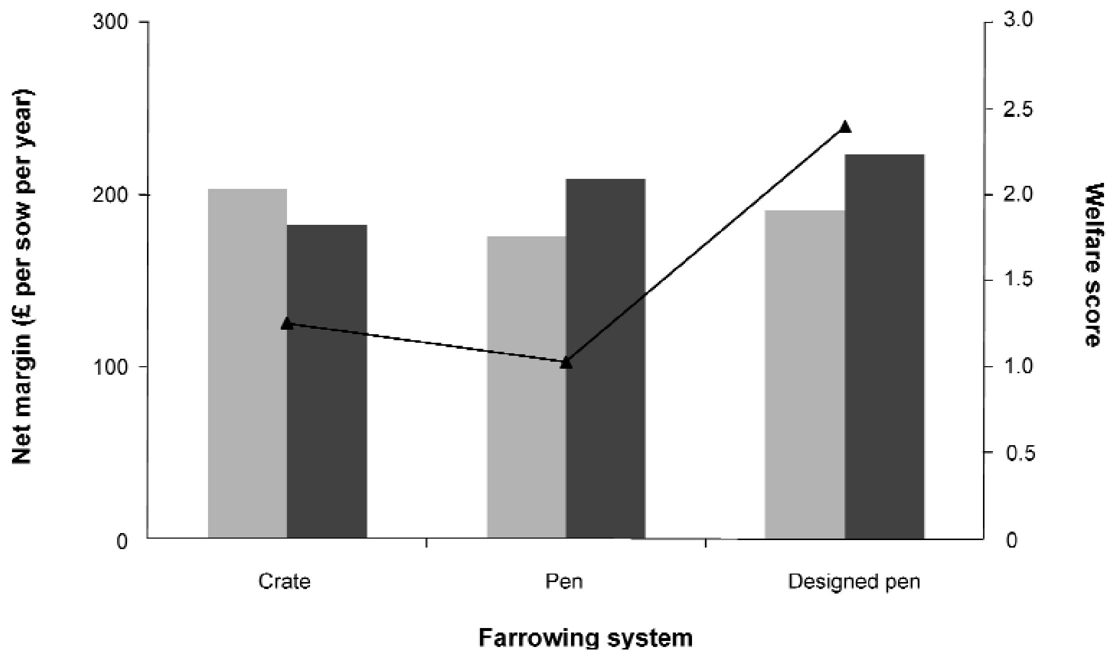
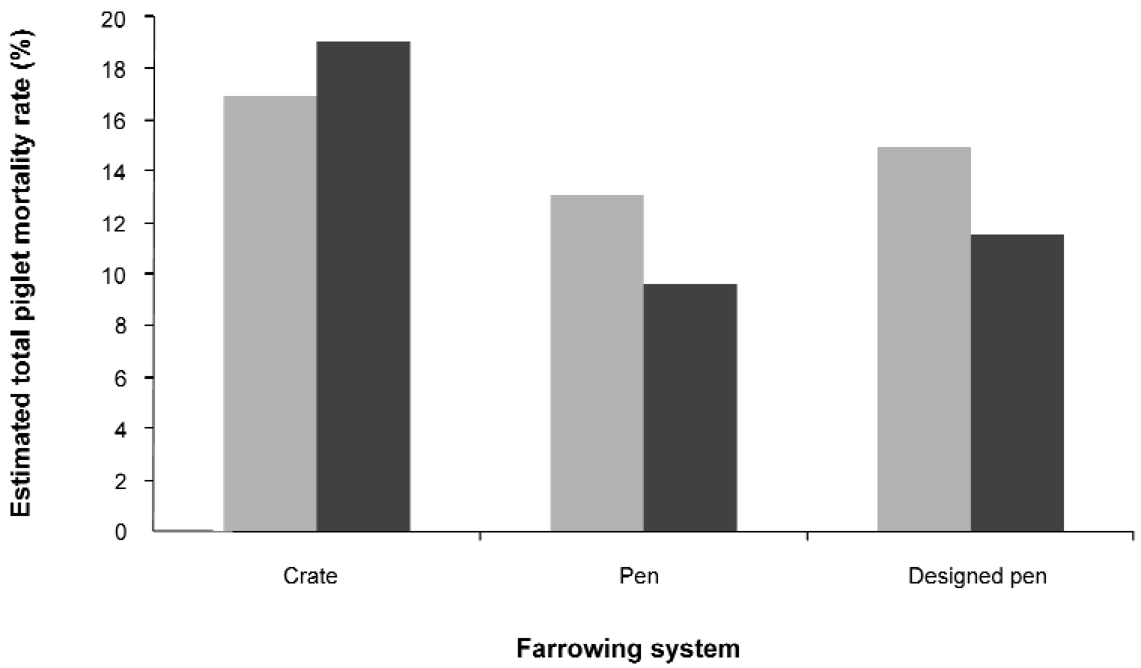
Figure 3



Net margins £ per sow per annum (bars) and welfare scores (line) for three studied farrowing systems estimated for two runs of the model: RUN1 (light bar) and RUN2 (dark bar). Costs of extra substrate, space and power were used in the LP for both runs.

Figure 4



Total piglet mortality rate for maximum profitability estimated by the LP model in RUN1 (light bar) and RUN2 (dark bar).

Piglet mortality

Outputs of the LP indicated that the crates generated the highest total mortality rate of 16.91% compared to the pens (13.07%) and the designed pens (14.89%) in RUN1 (Figure 4). An increase (up to 19.05%) in the crates' mortality rate was observed in RUN2. This was purely because of the adverse effect of the temperature production function on mortality rate in the crate system. On the contrary, mortality rates of the pens and the designed pens showed a reduction to 9.59 and 11.55%, respectively, in

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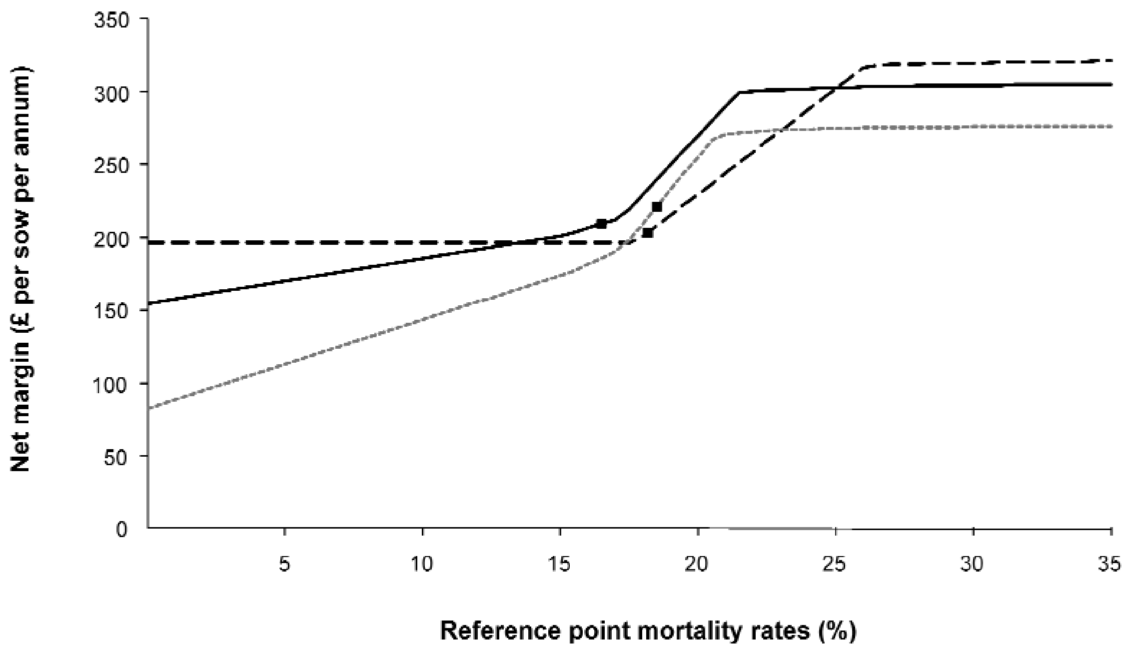
Figure 5



Sensitivity of predicted net margin (vertical axis) to changing reference-point mortality rate (horizontal axis) for the crates (large dashes), the pens (small dashes) and the designed pens (solid line). Square points show the default assumptions for the baseline mortality rates drawn from the literature and the corresponding net margins predicted by the LP. No additional cost for extra space was used for these runs.

RUN2, when constraints on mortality limits were relaxed. However, such low mortality rates are rarely achieved on commercial farms which justifies the constraints imposed to limit the maximum reductions in piglet mortality using WCs in RUN1.

Sensitivity analysis

Multiple LP runs were performed (assuming no additional costs for extra space) to examine the sensitivity of predicted net margin to reference-point mortalities for the three systems (Figure 5). No change in net margin of the crates was observed by increasing the reference-point mortality from zero up to 17.5%. Further increasing the reference-point mortality rates up to 28% raised the net margin to £319.00 as a result of the enhanced survival rate under RUN2. Net margins of the pens and the designed pens were improved by moving the reference-point mortality rates from zero towards and beyond the baseline reference-point mortality rates drawn from the literature (RUN1). For the pens and the designed pens, the highest net margin of £275.00 and £304.00, respectively were obtained at reference-point mortality rates of 25 and 27%, respectively. This reflects the important influence of the reference-point mortality rates (ie the initial mortality rate of the systems before introducing WCs) on the capacity of each farrowing system in improving mortality and the net margin.

Sensitivity of the designed pens to variations in WC (Figure 6) showed that increasing the quantity of the available substrate in all the three different levels of space, improved the net margin observed up to a maximum point, assuming no additional costs for extra space. In general, the predicted net margins followed a polynomial curve pattern. Utilising 13 kg of substrate per sow, when the minimum space level for the sow and piglet was provided, generated the highest net margin (£233.00) on this curve. Likewise, 13 and 14 kg of substrate were required to generate the highest net margins of £245.00 and £253.00 at the baseline and maximum space levels, respectively.

Discussion

This study was performed as part of the design process highlighting the main issues arising at the biological-economic interface and the first steps taken to address them. The production functions assessed by animal scientists, which were embedded in the model, allowed the LP to test possible trade-offs between profit and welfare within the studied farrowing systems mediated by marginal changes in WC. Based on presented results, the crates were more profitable than the pens under RUN1. This outcome was expected mainly because of the lower fixed costs (eg investment) and variable costs (eg labour) associated with crates. Under RUN2, piglet survival rates were enhanced in the

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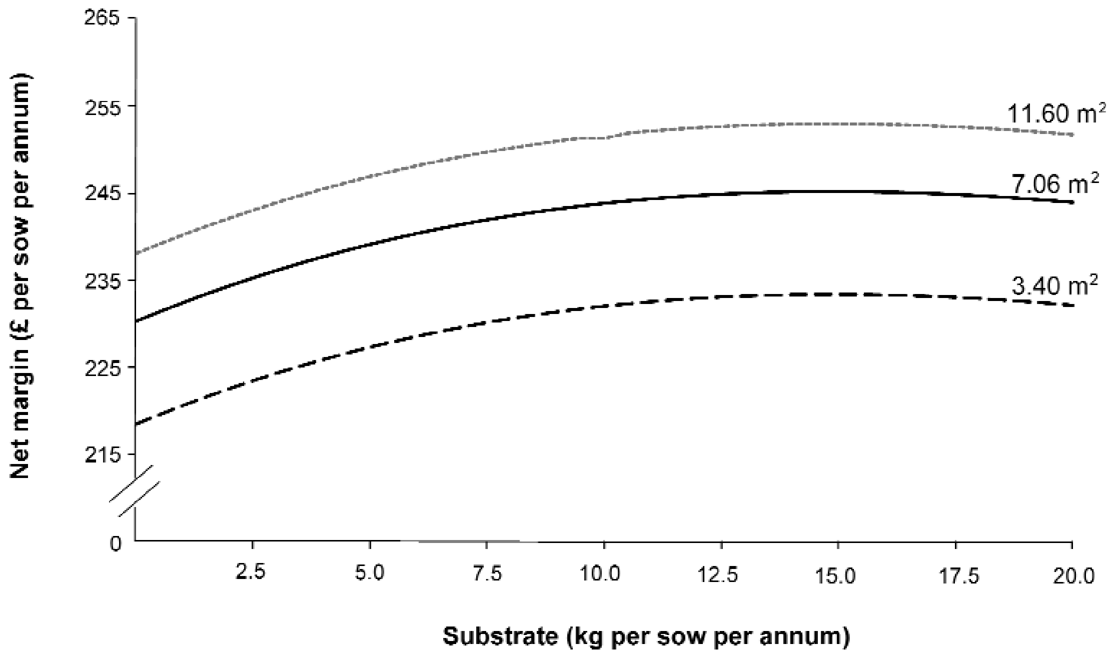
Figure 6



Effect of substrate use on predicted net margin £ per sow per annum for the designed-pens at three different levels of space: baseline (7.06 m^2 per sow and litter), minimum (3.40 m^2 per sow and litter) and maximum (11.6 m2 per sow and litter) based on the reviewed scientific publications and using the expert derived production-functions. No additional cost for extra space was used for these runs.

non-crate systems but for crates, the temperature-mortality function had a detrimental impact.

Results indicated that both the designed pens and the pens benefited from the production functions used in the LP, gaining a net margin big enough to overcome the crates' cost advantages. In RUN2, the non-crate systems outperformed the crates even though the full costs of the extra WCs, including extra space, were taken into account. This outcome is consistent with the findings of Cain and Guy (2006), suggesting that the higher cost of constructing and managing higher welfare systems may be offset by better animal performance. In practice, the marginal cost of extra building space should be lower than the initially estimated costs used in the LP as the cost of pen furniture and other related accessories will not increase in line with the extra floor space.

The designed pens provide higher welfare for sows and piglets compared with crates and pens, therefore these results imply the possibility of a win-win situation for welfare and economic aspects of this system provided that the extra WC can deliver the predicted improvements in piglet survival. However, due to uncertainty surrounding the production functions and the derived coefficients, these results need to be interpreted with care. The LP should be considered a framework with which to explore possible trade-offs between modifications for welfare and profitability at the design stage and not as a predictor of economic performance on implementation. The optimisation of the LP provides a benchmark for comparison both between and within farrowing systems. This ensures that all comparisons are based on the best combination of activities for each system and not under the usual *ceteris parabus* conditions that may, by chance, favour one system over another. The model presented, demonstrates the application of the approach suggested by Stott and Lawrence (2009) in combining economics and science to design systems that provide high animal welfare at least cost. We see no reasons why this approach could not be used to compare other options in pig and other livestock systems.

The superior economic performance of the designed pens and pens under RUN2 depended on the production functions to improve survival parameters above baseline, highlighting the difficulty of deriving such functions without reference to a specific farrowing system. In both scenarios presented, the pen system achieved the lowest total mortality rate (13.07% in RUN1 and 9.58% in RUN2). This was mainly because it utilises a relatively large amount of space (10.48 m^2 per sow) and substrate. In RUN1, this enhanced its capability to improve the survival of piglets up to the lower 95% confidence limit constraint on mortality based on observed variation in commercial farms. However, by relaxing this constraint in RUN2 the pens achieved a very low mortality rate with improved net margin. The probable influence that these environments have on

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maternal behaviour is responsible for this improvement: suitable substrate and space facilitates satisfactory nest-building behaviour, with feedback from building and completing a nest affecting neuroendocrine regulation of maternal behaviour during farrowing (Damm *et al* 2003; Algers & Uvnäs-Moberg 2007). The lack of substrate and space in farrowing crates has been shown to preclude nest-building activity and increase physiological stress responses in sows (Lawrence *et al* 1994; Jarvis *et al* 1997) which, in turn, can negatively affect maternal behaviour (eg increased risk of savaging — Cronin *et al* 1996; Jarvis *et al* 1998). Further studies have specifically implicated the lack of space as a major influence on stress responses of peri-parturient sows (Jarvis *et al* 2002). Based on the LP estimation, there was a capacity for the designed pens to improve mortality rate from 14.88 to 11.55% by using the interactions between the WCs. This observation could be tested in experimental studies.

Given the mentioned assumptions and methodology used, sensitivity analysis on the reference mortality rates indicated that, in general, the pens and the designed pens had more scope to improve piglet survival via extra WCs and hence gain better net margins than the crates. This effect was more prominent when the reference mortality rates were below the baseline drawn from the literature. However, at reference mortality rates beyond 22%, the crates were the most successful system in improving the survival rate. This point highlights the need for generally good performance to get the best from non-crate systems. Crates may provide an acceptable net margin over a wider range of mortalities, ie they are less risky and less demanding of stockmanship and management. This feature of crate systems was partly attributable to their positive effects in reducing mortality rate as a result of using the temperature-mortality production function (equation 3). This example showed that the results were particularly sensitive to the temperature-mortality production function. Further analysis based on experimental data is therefore required to validate the assessed temperature-mortality function in particular.

Results of sensitivity analyses also implied that different utilisation levels of WC can affect the maximised net margin in the designed pens. Using the average literature values for the input parameters (Table 1) and assuming no additional costs for extra space, the designed pen generated £236.00 profit per sow per annum (baseline space curve in Figure 6). The maximum net margin on this space curve was equal to £245.00 which was attained by providing 13 kg of substrate per sow. Exceeding this limit would suppress the profit because of its counter-productive effect. This curve was shifted upward by increasing the available space and pushed down by decreasing it. The maximum space setting generated £253.00 at maximum substrate of 14 kg and the minimum space setting achieved £233.00 at 12 kg of substrate. From the economic point of view, given the much cheaper costs of substrate than space and considering the fact that the cost of marginally increased space has not been directly included in this estimation, it is more financially beneficial to move towards the right-hand side on the minimum space setting curve. Utilising extra substrate incurs extra costs, such as extra labour in provision and cleaning as well as extra environmental costs. These costs were not included in the presented LP. In addition, the break-even costs of extra building space (ie the cost needed to make the net margin of the designed pens equal to the net margin of the crates) was estimated at £7.50 per sow per annum. By taking these costs into consideration, other points on the presented curves in Figure 6 could have presented optimum combinations. However, from the animal welfare perspective the maximum and the average space curves may better address animal welfare needs. Thus, a compromise is needed to establish acceptable trade-offs between profit and welfare within the farrowing system. This trade-off may be affected by interactions between WCs, which were ignored in this study due to lack of information and to avoid a more complex model. Other WCs may also be brought into the mix. For example, labour quality and quantity will affect the production functions used here and are in themselves WCs. It must be noted that economic performances of the farrowing systems and the costs of providing additional welfare components presented were based on UK conditions. These figures are likely to be different across other countries and therefore the outcomes and conclusions may not be immediately applicable to other economic situations.

Conclusion

This interdisciplinary study combined an economic optimisation technique and animal welfare science as part of the design process to test possible trade-offs between profit and welfare within three alternative farrowing systems: crates, pens and designed pens. Results of the model runs indicated that using literature-derived baseline piglet survival rate as a reference point in the model and incorporating the costs of extra WCs (ie substrate, space and power) in the model, crates obtained the highest annual net margin and the designed pens and the pens were in second and third place, respectively. The designed pens and the pens were able to improve their annual net margin once alternative reference points were used to adjust piglet survival rates in response to extra space, extra substrate and modified pen heating following expert-derived production functions. The designed pens then provided higher welfare and higher net margin for sows and piglets than the crates and the pens, suggesting the possibility of a win-win situation for this system.

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