Generating estimated breeding values for postnatal lamb survival

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Background

The survival of lambs in extensive sheep production systems is a major contributing factor to the economic efficiency of these farms and is an indicator of good animal welfare. Estimates of lamb pre-weaning mortality vary considerably between 10 and 30% and most of these mortalities occur within the first 3 days of postnatal life (various publications cited by Dwyer, 2007). For Blackface sheep in the UK, estimates of 10%, 15% and 30% for single, twin and triplet-born lambs, respectively are reported (Conington et al., 2004), hence including litter size born as a breeding goal trait in livestock breeding programmes increases the number of offspring born over time, but decreases their chances of survival.

Improving lamb survival through management and breeding methods has been the subject of several studies in the past. Improving lamb survival through breeding is very relevant for extensively-managed flocks such as hill breeds, or for flocks where minimal intervention by man is practised. This is because it identifies individuals and families of sheep that differ in their inherent ability to lamb unaided, nurture and rear their young, as a well as identifying offspring that are less viable at birth, vocalise less and potentially, those that have either very low or very high birth weights (Conington et al., 2010; Dwyer and Lawrence, 2005, Dwyer 2007).

The current hill sheep breeding index ('Hill2') that is delivered by Signet to hill sheep farmers in Scotland and England (after Conington et al., 2001) replaced the 'number of lambs born' trait with 'number of lambs reared'. This shift in emphasis towards the ability of the ewe to rear what she produces reduces the 'wastage' of lambs lost in the economically important time period to weaning, after which the main decisions for breeding and sale of lambs are made.   However, subsequent analyses showed that additional benefits would be apparent if lamb survival was directly attributed to the lamb ('direct' lamb survival) reported by Conington et al (2002; 2007) as long as the additional costs of recording the information did not outweigh the benefits.

Using the live weights of lambs recorded at the strategically important time periods (i.e. Signet's 8 week and 21 week scan weights) is a way to identify lambs that are still alive, as long as any live lambs that fail to be weighed at the allotted time period are known and recorded. Lamb live weights at birth are an important factor in the model used for the prediction of EBVs for lamb survival (Sawalha et al., 2007), yet not all hill flocks record this trait. Knowledge of the mathematical function between survival and subsequent 8 and 21 week live weights is needed, to ascertain if recording live weights at birth is necessary for accurate Survival EBV predictions.

The definition of 'survival' can be interpreted in different ways and as such, influences the genetic parameters that are associated with each definition. Sawalha et al (2007) report genetic parameters for survival, explicitly according to different time periods from birth, but they cannot be extrapolated for use by the sheep industry without additional recording and new data generation. Research into the definition of the most relevant survival trait is required in the context of current sheep breeding programmes. This will then generate relevant genetic and phenotypic parameters that can be used in the estimation of EBVs for lamb survival.

Economic benefits of improving lamb survival

We estimate that with a UK ewe population of 15.5M (Defra, 2011), lambing rate of 1.2 lambs born (dead and alive) and 15% mortality, then the cost to the UK is likely to be more than £181M per annum assuming an average lamb price of £65. Even at low rates of annual genetic improvement of 0.5%, assuming these benefits are realised throughout the entire ram breeding industry, this will lead to a reduction in the economic cost of lamb mortality of around £6M per annum to £175M per annum.

For the Blackface breed alone with around 1,093,000 breeding ewes (Pollot, 2005) assuming a lower price/head at £60/head, the costs of lamb mortality are almost £11.8M. The benefits of implementing genetic improvement in this breed, again assuming these benefits are realised throughout the Blackface ram breeding industry are potentially, around £400,000 per annum.

Objectives of this study

The overall objective is "*To evaluate the possibility of generating meaningful estimated breeding values for lamb survival (defined as a lamb having been reared) using existing data for one large, well recorded population*".

The specific objectives of this proposal are:-

1. To collate industry data from the BASCO database for the Scottish Blackface breed and to edit for outlying records for key records (e.g. records recently extracted for another breed has data showing age at 21 week weight to be up to 522 days and such anomalies require editing to obtain sensible parameters).

2. To run connectedness software to determine if it is appropriate that all flocks can be evaluated together and combined to form a single dataset for parameter estimation.

3. To investigate the trait 'survival from live birth to 8 weeks' and using information from scan weights to 'catch' additional data that could be lost if only 8 week weight is used (this is due to imperfect gathering of lambs for hill flocks at this time, and other lambs that are 'missed' at the 1st weighing occasion). This includes documentation of rules to be applied for data extraction and evaluation to avoid false lamb deaths.

4. To quantify this trait (estimate univariate predictions of phenotypic and genetic variances) for direct and maternal components for these data The work will include testing the most relevant model for genetic evaluations (i.e. determine which key fixed and random effect data are required for the best predictions of parameter estimates).

5. Using existing data for current genetic evaluations, estimate genetic and phenotypic variances and co-variance parameters (genetic correlations) for the existing breeding goat traits with lamb survival, in readiness for the multivariate commercial implementation of EBVs for lamb survival. This exercise will update existing

parameters used for the genetic evaluations thereby negating the need for Signet to do this for the Blackface breed in the near future.

6. Compare results from records where birth weight is available vs unavailable, and (where possible) for flocks that either do, or do not lamb out of doors. (This will involve Signet to provide SAC with such information).

7. Hold two half-day meetings with Signet before and after the work is completed.

8. Write final report and a technical note in layman's language to explain the derivation of lamb survival EBV and how to interpret the information. This can then be edited by Signet for use in farmer training sessions. The final report will outline all required information to implement the lamb survival EBV so that EGENES can then replicate it in the live system.

Methodology

1. Connectedness evaluation

The connectedness software used by EGENES to evaluate the connectedness among the flocks was used to undertake a routine analysis of the status of connectivity among the whole Blackface breed as well as 20 of the currently active flocks.

2. Lambing indoors vs lambing out of doors

A questionnaire (See Appendix 2) was sent to currently recording Blackface flocks to determine which flocks lamb entirely out of doors, and which lamb indoors or a combination of the two. Six key questions were asked and the flocks were coded 1 if they lambed out of doors entirely, 2 if they lambed indoors and 3 if they lambed partially indoors. This information was used for a subset of the data from 22 flocks that responded to the questionnaire and which also had data that fell within the quality criteria for the analyses (see below).

3. Survival analysis

Data cleansing

Data from Signet's Sheepbreeder performance scheme held on the BASCO database for the Blackface breed was investigated for this study. The total (un-cleaned) data set comprises a total of 232,805 individual animal records.

The data were cleaned to comprise records that:-

- Were 100% Blackface breed
- No cross fostering
- No recipient / surrogate or different rearing dam to genetic dam
- Flocks had at least 500 records and both had dead as well as live lambs.

- Only animals born into the flock used (i.e. animals brought into the flock were not included).

Data problems: There were many records that were deleted from the data set due to irregular / impossible values. Fifty eight identities were also removed from the data with irregular pedigrees.

Key point:

Only lambs born dead have been registered as such, since 2007. A disproportionate number of ‘born dead’ lambs (n= 783 out of a total of 1480) are recorded as being castrates.

Cleaned data set

The data set comprised 173,895 lamb records for each year from 1976-2011 (36 years of data) i.e 75% of available data were suitable for analysis. The data were then filtered further for the genetic parameter estimation only, with only lambs born in 2000 or afterwards being included. This reduced the data set size to 89,819 lamb records with 29,532 dams. Further, the ‘2007 onwards’ data included 27,111 lambs with survival records.

Definition of Lamb survival trait and statistical analysis

The data were not suitable to undertake a formal time-series ‘survival analysis’, because the actual dates of death or disposal from the flock are not recorded in the database. Two different methods were used to define the lamb survival trait. First, the lamb survival trait was coded 0=dead if any lamb recorded at birth subsequently had no live weight recorded at either 8 weeks (early weight) or subsequent weighing occasions (scan weight), and 1=alive, if it survived at least until 8 weeks so that a binomial analysis of this trait could be used. Second, as lambs born dead have only been recognised in the database since 2007, data for lambs born 2007 onwards that were recorded as having been ‘born dead’ (denoted with a ‘#’ in flock book identity in BASCO database) were coded as 0=born dead. Lambs that were born, but not identified as being dead and did not have any subsequent live weights recorded were coded 1=dead, and lambs that were born and also had subsequent weights were coded 2=alive (see Table below).

	0	**1**	**2**
SURV01	**Dead** - Born dead and lambs born alive but no subsequent live weights	**Alive** – lambs with live weights	-
SURV12 (2007+)	**Dead** - Born dead only	**Dead** -Born alive but no subsequent live weights	**Alive** – lambs with live weights

The data were analysed first using the GENSTAT statistical package using a Generalised Linear Mixed Model (GLMM) for binomial trait distribution using a logit transformation function where the regression fitted generates the coefficients of a formula to predict a logit transformation of the probability of presence of the characteristic of interest (lamb survival):

Logit (p) = $b_0 + b_1X_1 + b_2X_2 + b_3X_3 \ldots b_nX_n$

Where p is the probability of presence of survival and X is the explanatory variables (e.g. flock, sex, age of dam etc). The transformation is defined as the logged odds is

$$odds = \frac{p}{1-p} = \frac{probability\ of\ survival}{probability\ of\ death}$$

And

$$logit\ (p) = \ln\left[\frac{p}{1-p}\right]$$

The logistic regression maximises the likelihood of observing sample values and this was used to quantify the key factors affecting lamb survival and for the genetic evaluations.

The genetic analyses were performed using ASREML statistical software using univariate analyses including flock-year-season-sex, dam age, litter size and birth weight (covariate) as fixed factors and including random effects of lamb (a^2), dam (m^2), and dam as permanent environment (C^2).

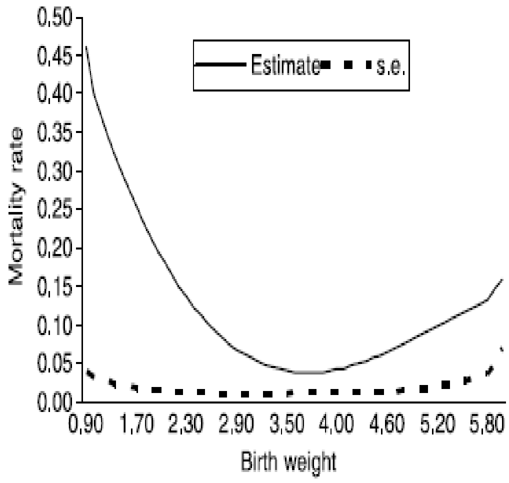
4. *Genetic analyses and parameter estimates*

Genetic variances and heritabilities for each trait were also performed using ASREML software. Where appropriate, the different models fitted reflect the type of trait that is being analysed. It’s important to remember, that where survival is being analysed with the other traits, it is only lambs which survived that actually have phenotypic records for these traits. Genetic correlations are therefore estimated through the genetic relationships amongst the population and no phenotypic correlations are reported.

Birthweight vs excluding birth weight

The survival data were analysed both with and without fitting birth weight in the analyses. The total number of birth weight data = 49,917 and hence the difference between parameters may reflect the difference in the data set size (*vs* 173,895) rather than the true impact of including birth weight into the model. The relationship between birth weight and lamb mortality rate in Blackface sheep was reported in 2007 by Sawalha et al., which showed that there is an intermediate optimum birth rate below and above which mortality rates are increased (see Figure 1 below). In this study we examine the impact of including and excluding birth weight on other factors in the model. This then better disentangles the 'true' impact of each explanatory factor.

Figure 1: Relationship between birth weight and mortality rate in Blackface sheep[1]



[1] Taken from Sawalha et al., 2007

Other traits

The other 10 traits that were analysed include early (8 week) weight (8 wk), scan (21 week) weight (21 wk), fat depth (FD), log-transformed fat depth (lnFD), muscle depth (MD), mature size (MS) faecal egg count (strongyles) (FECS), log-transformed faecal egg count (strongyles) (lnFECS), faecal egg count (nematodes) (FECN), log-transformed faecal egg count (lnFECN). An additional trait, birth weight (BWT) was also analysed as part of the analyses.

The models used to re-evaluate these traits are the same as those used for the routine genetic evaluations performed by SAC on behalf of Signet. They are shown in Appendix Table 1. A repeatability model was used for the maternal trait evaluations as there were multiple records for the same ewe. (This essentially captures the partition of variance attributed to the non-genetic dam effect.)

Results

1. Connectedness evaluation for Blackface Sheep, August 2012

Based on the last live evaluation of 2011 (batch id 20080913) a connectedness summary was produced. This summary showed that there were 100 different flocks recording 8 week weight since 2000. However, only 20 of these flocks are currently active.

Table 1 below shows a summary of the connectedness values for SBF breed. When all 100 flocks are considered and using the current threshold values, 65% have low connectedness, 27% have sub-optimal connectedness and only 8% of flock have acceptable connectedness levels. The current threshold levels are above 0.025 to be well connected and below 0.0125 is lowly connected. Recent research has showed that these values are actually too low and the thresholds should be above 0.10 to be well connected and below 0.05 is low connectedness. If we were to apply these new recommended thresholds then all 100 flocks would be lowly connected. While connectedness across the whole breed is generally very low when the pair-wise comparisons are considered there are some flocks that are well connected; for example there are 2 flocks that have a connectedness value of 0.53.

Table 1.1: A summary of the connectedness values[1] for SBF when all flocks are considered

	connectedness value across flocks (ave rij)			Connectedness level %			Pair wise comparisons – maximum value (rij)		
N flocks	**Average**	**Min**	**Max**	**Low**	**Sub**	**OK**	**Average**	**Min**	**Max**
100	0.01	0.00	0.04	65	27	8	0.14	0.00	0.53

[1]Rij =connectedness statistic

Table 1.2 below shows the connectedness summary for SBF breed when only the 20 active flocks are considered. Connectedness is generally higher when only the active flocks are considered; with 80% of flocks being well connected with the current thresholds. However, if the recommended thresholds are applied then no flocks will be well connected and 90% are classed as low connectedness.

Table 1.2: A summary of the connectedness values for SBF for the 20 active flocks

	connectedness value across flocks (ave rij)			**Connectedness level %**			**Pair wise comparisons – maximum value (rij)**		
N flocks	**Average**	**Min**	**Max**	**Low**	**Sub**	**OK**	**Average**	**Min**	**Max**
20	0.03	0.00	0.05	1	3	16	0.14	0.03	0.49

These results show that there is a connectedness issue with the SBF and that the active flocks should work on increasing the connectedness values between themselves. Although still being decided it is likely that in the very near future the connectedness reports will consider only active flocks and the connectedness thresholds will be raised either to the recommended levels or a temporary intermediate thresholds.

At the current threshold levels, it was appropriate that the majority of the current flocks be evaluated together for the EBV for lamb survival to be generated. However, at the higher recommended threshold levels, the lack of connectedness may impact on these results but it is not known to what degree.

2. Survey summary

A total of 25 respondents provided information about their main management methods at lambing time. Twenty two of these flocks also had data within the data set that met the quality criteria.

The results from the questionnaire are shown in Table 2.1below

Table 2.1: Summary information for questionnaire

Question	Description	No. respondents	Percentage
1	All recorded ewes are housed for the duration of lambing	3	12
2	All recorded ewes are lambed outdoors	18	72
3	Some lamb indoors, some lamb outdoors (see (8) for details)	3	12
4	All are lambed outdoors during the day and indoors at night	1	0.04
5	Other (see (8) for details)	1	0.04
6	Has the policy indicated (in (1) to (5)) above significantly changed in the time you have been perf. recording? (Y/N)	No = 22 Yes = 1 Blank = 2	No = 88 Yes = 0.04 Blank = 0.08

Two of the flocks that responded were not included in the data set because their data did not fall into the data quality threshold. The farms were subsequently coded into 3 categories: 1= lambing outside, 2=lambing inside and 3=lambing partially in and out (categories 3-5). This 'in-out' category was fitted into the survival model in GENSTAT to determine if it was a significant influencing factor on survival. However, there was no significant effect whatsoever on lamb survival, and because of this, it was dropped from the model altogether.

3. Survival analyses

An overview of the 12 traits in the data that were analysed is shown in Table 3.1.

Table 3.1: Summary statistics for the traits analysed

Trait	No. records	Mean	s.d.	min	max
Survival0/1	173,895	0.88	0.33	0	1
Birth weight kg	49,417	3.8	0.72	2.0	9.0
8 week weight kg	151,842	20.9	5.4	6.8	55.8
21 wk weight kg	73,080	30.6	6.9	10	69.8
fat depth mm	71,791	2	1.16	0.1	12.5
log fat depth	71,791	0.56	0.56	-2.3	2.4
Muscle depth mm	71,838	21.6	3.6	9	37
FECS	1,676	364	537	0	6,590
Log FECS	1,676	5.15	1.45	-1	8.85
FECN	1,676	116	228	0	2,250
Log FECN	1,676	3.85	1.61	-1	7.7
Mature size	22,416	48.6	5.9	22	85

The number and percentage of lambs according to the survival trait definitions are summarised in Table 3.2. The overall percentage of lambs in the database that did not have 8 week or 21 week weights (i.e. attributed as '0' in the survival trait data) was 12.2%. This suggests that there could be under-reporting of lambs that were born but were not given an identity in the database for realistic lamb survival statistics to be generated. Alternatively, the flocks that are recording may have higher than average survival rates compared the typical range of 10-30% for lamb mortality from several studies cited in a review by Dwyer (2007).

Table 3.2: Survival classes according to survival trait

	0	1	2
SURV01 (all data)	21,254 (12.2%)	152,633 (87.8%)	-
SURV01 (2000+)	9,083 (10.1%)	80,736 (89.9%)	-

SURV12 (2007+)	1,480 (5.5%)	1,836 (6.7%)	23,795 (87.8%)

A very small proportion of the whole data set (0.008%) were recorded as been 'born dead', which suggested that some key data important for lamb survival are missing. However, further investigations revealed that only lambs born after 2007 were identified has having been born dead.

The analyses showed that the main factors affecting lamb survival include flock, year/season, age of dam, sex of lamb, birth rank and birth weight (covariate). Year/season was fitted as random effects together with dam of lamb for these analyses (hence not reported in the table below). All significantly affect lamb survival (P<0.001) (Table 3.3).

Table 3.3 : Table of significance of effects from GLMM analyses (logit) for lamb survival

Fixed term	Wald statistic	d.f.	F statistic	d.d.f.	F-Prob
sex	138.54	2	69.27	49709.6	<0.001
litborn	107.26	3	35.75	49819.9	<0.001
new_dage	168.94	9	18.77	49843.8	<0.001
Flk*	349.24	28	12.45	7000	<0.001
bwt	265.27	1	265.27	49258.4	<0.001

*Only 29 flocks had birth weight recorded

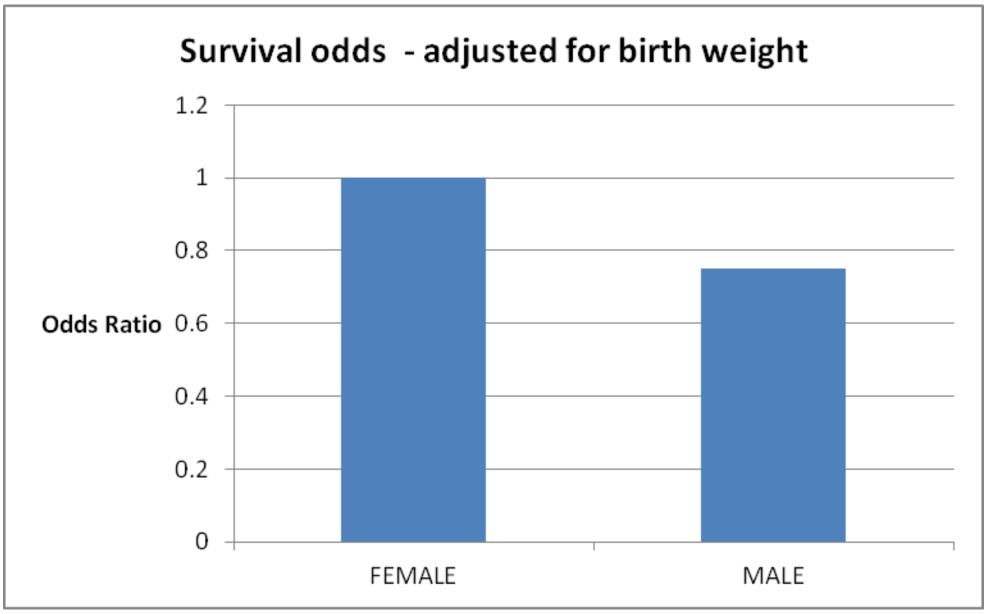
The data showed clear differences in the 'non-survival' rate of male vs female lambs, being 11% and 15% of male and female lambs respectively. Interestingly, the non-survival rate (6.8%) for castrated lambs was significantly lower than male or female lambs. This more than likely reflects management practices, that only lambs that have survived in any case up to the point of castration, were selected to be castrated. The data for castrated and entire male lambs were combined to generate only 2 sex classes to better compare overall survival for male vs female lambs. Table 3.4 and Figure 2 show the results for sex of lamb.

Table 3.4: Odds ratio (exponential of effects) for males vs female lambs[1]

Female	Male	Lower critical level	Upper critical level	95% CI[2]
1	0.75	0.704129	0.792466	*

[1]Data are adjusted for the key effects shown in Table 3.3 above. The interpretation here is that female lambs are 1.3 (1 / 0.75) times more likely to survive compared to males. The lower and upper critical levels are given for the 95% confidence interval for the odds ratio. (The closer they are, the greater the confidence in the result. If they straddle 1, then the result is not significant). *Standard error of difference (s.e.d.) = 0.03. [2]95% confidence interval (CI): NS=Not significant, * significant.

Figure 2: Survival of Male vs Female lambs



To get a clear picture of the influence of birth weight on other traits in the model, the model was run with and without birth weight and the results of the impact of being born as single, twin and triplet are reported in Table 3.5 below.

Table 3.5: Odds ratio for (exponential of effects) for survival according to litter size born, **without** adjustment for birth weight[1]

Litter size	**1**	**2**	**3+**
Odds*	1	0.85	0.41
Lower critical level	0.66	0.57	0.27
Upper critical level	1.29	0.61	0.60
95% CI	NS	*	*

*The results show that singles are (1/0.85) 1.18 times more likely to survive compared to twins, which in turn are (0.85/0.41) 2 times more likely to survive compared to triplets. Mean s.e.d. = 0.21.

We are more used to assuming that higher litter sizes incur higher losses, as these results (also shown graphically in Figure 2) show clearly that compared to singles, twins have a poorer chance of survival compared to singles. However, in order to compare whether or not this is due mainly because of the average size difference at birth, live weight at birth was also fitted in the model and the results of this are shown in Figure 3 below. The results now tell a different story to those shown in Figure 2 and the improvement in the chances of survival if twin-born is probably a reflection of the very different management strategies that are often put in place to enable hill farms to preferentially manage twins (often reared on improved grassland areas).

Figure 3: Survival of litter size born – without adjustment for birth weight

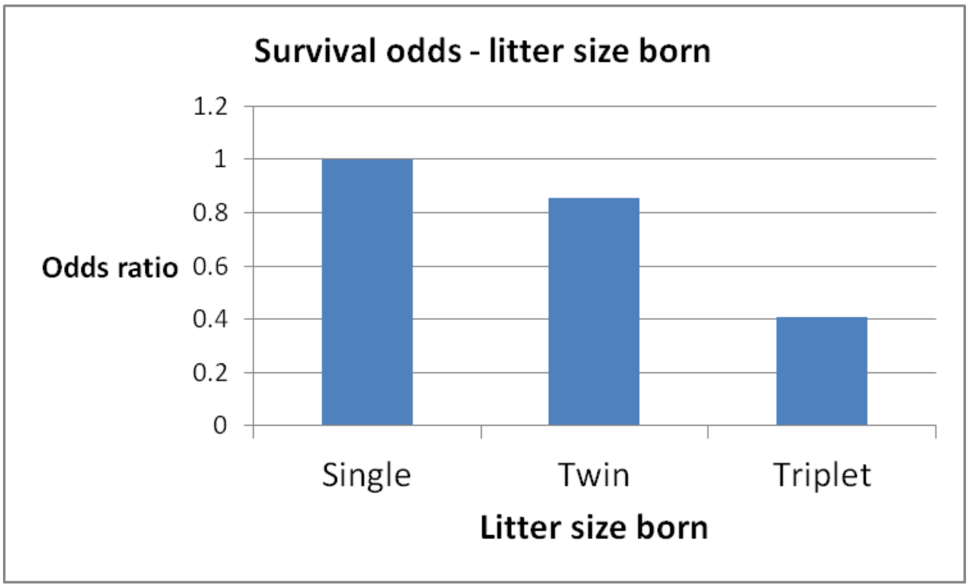
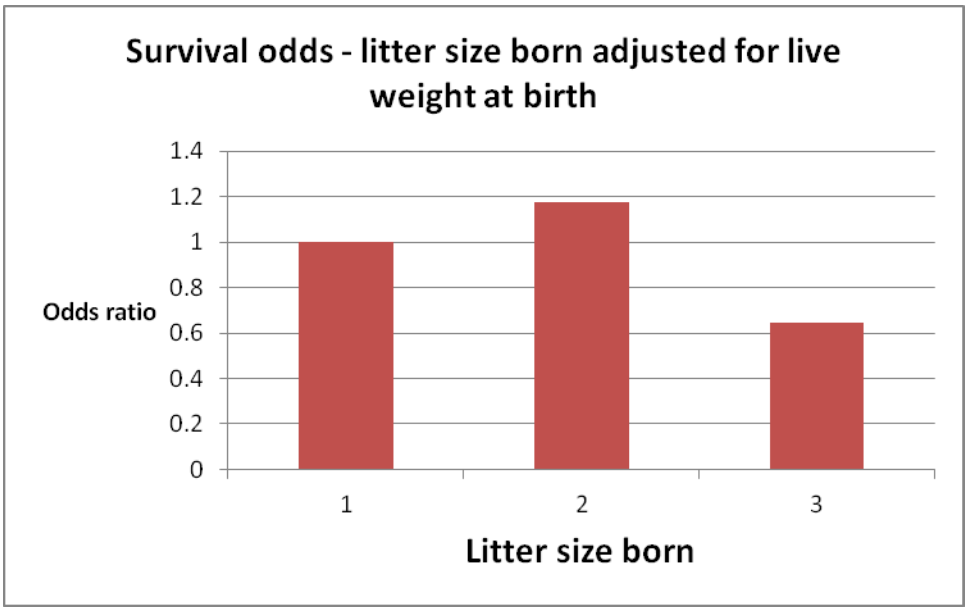


Figure 4: Survival odds of litter size born[1] adjusted for birth weight



[1]Compared to twins, single lambs are (1/1.17) 0.85 times likely to survive and compared to triplets, twins are (1.17/0.64) 1.8 times more likely to survive.

The age of the dam has a key influence on the performance of her offspring and this is shown in Table 3.6 and also seen in relation to survival (Figure 5). The results are expressed in relation to 1 year old ewes.

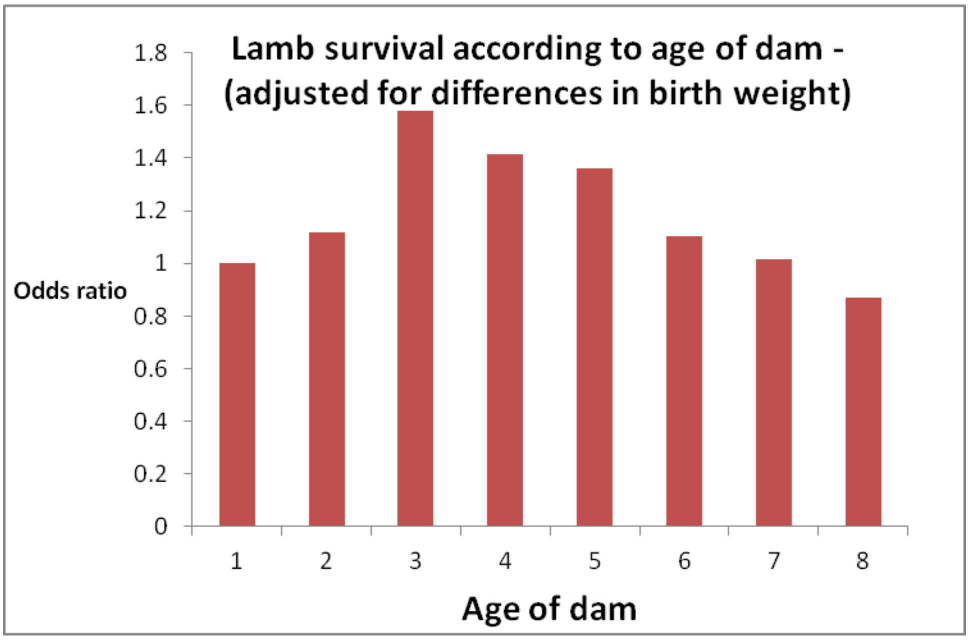
Table 3.6: Odds ratio for survival according to ewe age, adjusted for birth weight[1]

Ewe age	Odds ratio	lcl	ucl	95% CI

1	1	0.49	2.04	NS
2	1.11	0.55	2.28	NS
3	1.57	0.77	3.23	NS
4	1.42	0.69	2.89	NS
5	1.36	0.67	2.78	NS
6	1.1	0.54	2.26	NS
7	1.01	0.50	2.07	NS
8	0.87	0.43	1.78	NS

[1]average s.e.d = 0.36

Figure 5: Survival odds according to the age of dam[1]



[1]lambs from 3 year old ewes are (1.58/1.11) 1.4 times more likely to survive compared to lambs from 2 year old ewes and have the highest likelihood of survival compared to all other dam ages. However, the odds ratios were not statistically different from 1.

4. Revised parameters

The survival trait was analysed using different models to compare the variance components. The results for some of the models tested are shown in Appendix 3 and the suggested models for producing EBVs in Table 4.1a. Including both direct and maternal genetic components of variance yielded the highest total heritability when the data were restricted to years 2000+. Having both (maternal as well as direct) EBVs for lamb survival together is likely to improve the rate of gain in this trait. However, lamb survival as defined from the Blackface data set has a low heritability and as such, there would be little benefit to estimating genetic correlations of lamb survival as currently defined, with the other traits in the index.

When the parameters were estimated for the SURV12 trait, there was little discernible difference in the variance components and are therefore not reported here. Restricting the data set to 2000+ and 2007+ had less of an impact on the variance component estimations compared to the model use for the analyses. The EBVs for lamb survival have been generated for the animals in the cleaned data set used to derive the genetic parameters and would be available for the industry (although are not included in this report).

Genetic parameters were also estimated for the existing traits although are not reported here. Some of them were quite different to those shown in Appendix 1 and further analyses/ breakdown of the data is required to understand more fully why this this the case. Importantly, the main live weight traits had lower genetic than is normally expected for these traits. It may be necessary to re-structure the data set even further, to ascertain why these are very different to those that are currently used.

Table 4.1a: Variance and heritability estimates (s.e.) for lamb survival according to two different genetic models using different random effects*

	Direct	**Maternal Genetic**	**PE**	**Resid**	**Phenotypic**	**h^2_{direct}**	**$h^2_{maternal}$**	**h^2_{pe}**	**h^2_{total}**
SURV01 (2000+)	0.1800	-	-	3.2899	3.4699	0.0519 (0.015)	-	-	0.052
SURV01 (2000+)	0.0539	0.2884		3.2899	3.6322	0.0148 (0.006)	0.0794 (0.004)	-	0.094

*The interpretation of this result, is that the total heritability of lamb survival is between 5 and 9% depending on the model used in the analysis. Omitting maternal variance components would over-inflate the direct lamb heritability.

Recommendations for including lamb survival into the Blackface breeding programme

The amount of genetic variation for lamb survival as defined in this study is small. However, including it into a breeding programme would best be undertaken as a univariate trait (i.e. with the assumption that it is not correlated to the other traits) in the first instance.

Separating lambs born dead from lambs born alive, that died before being weighed had no impact on the variance components. Hence, using a binary analysis for lamb survival, given the current data collected is sufficient for this breed.

Treating lamb survival as a direct trait rather than as a trait of the ewe enables the separation between a lamb's own genes for survival to that of it's dam. Combining them both (i.e. providing EBVs for direct and maternal lamb survival) is likely to improve the rate of progress in this trait, although progress will be slow. Finding proxy traits for lamb survival (e.g lamb vigour at birth) may help to accelerate genetic selection for improved lamb survival.

Appendix 1

Current fixed effects and genetic model details for Blackface sheep genetic evaluations (June 2012)

	Fixed class effects					*Co-variate effects*			*Random effects*		
	Flock| season| sex	**Flock| season| sex| management group**	**Litter| flock| sex**	**Litter size reared**	**Dam age**	**CT_age**	**Ewe age at scan * Flock| season| sex**	**Scan age * Flock| season| sex| management group**	**Animal**	**Dam**	**Litter**
8 week weight	Y			Y	Y				Y	Y	Y
21 week weight		Y		Y	Y			Y	Y		Y
US muscle depth		Y		Y	Y			Y	Y		Y
US fat depth		Y		Y	Y			Y	Y		Y
Maternal_swt	Y			Y	Y		Y		Y	Y	Y
Mature size	Y								Y		
Litter size reared			Y		Y				Y	Y	
CT_ lean		Y		Y	Y	Y			Y		
CT_ fat		Y		Y	Y	Y			Y		
Lfec_S		Y		Y	Y			Y	Y		
Lfec_N		Y		Y	Y			Y	Y		

Variances and heritability estimates

Trait	Direct	Maternal	PE	Residual	Phenotypic	h^2_{direct}	$h^2_{maternal}$	h^2_{pe}
8 WK	0.741	0.995	1.351	3.297	6.384	0.12	0.16	0.21
SWT	3.767	-	2.146	6.892	12.805	0.29	-	0.17
MD	1.620	-	0.5492	2.8	4.969	0.33	-	0.11
FD	0.117	-	0.115	0.40	0.632	0.19	-	0.18
MAT	1.286	0.1358	0.4714	10.913	12.806	0.10	0.01	0.04
MS	10.077	-	-	13.445	23.522	0.43	-	-
LSR	0.028	0.17	-	0.368	0.566	0.05	0.30	-
CT_L	0.94	-	-	2.365	3.305	0.28	-	-
CT_F	1.404	-	-	3.436	4.84	0.29	-	-
FECS	0.12	-	-	0.68	0.80	0.15	-	-
FECN	0.06	-	-	0.24	0.30	0.20	-	-

* all co-variances between maternal effects are 0

Litter effect Covariances (below) and correlations (above)

	8 WK	SWT	MD	FD	MAT
8 WK		0	0	0	0
SWT	0		0.83	0.64	0
MD	0	0.8998		0.51	0
FD	0	0.3199	0.1272		0
MAT	0	0	0	0	0.4714

Direct Covariances (below) and correlations (above)

	8 WK	SWT	MD	FD	MAT	MS	LSR	CT_L	CT_F	FECS	FECN
8 WK		0.5	0.09	0.13	0.07	0.33	0.13	0.39	0.37	-0.13	0.17
SWT	0.835		0.19	0.27	0.15	0.65	0.27	0.48	0.5	-0.14	0.18
MD	0.102	0.462		0.53	-0.02	0.31	0.09	0.55	0.2	-0.05	0.22

FD	0.039	0.176	0.232		-0.03	0.3	-0.14	0.19	0.7	-0.05	-0.01
MAT	0.072	0.324	-0.035	-0.01		0.27	0.32	0	0	0	0
MS	0.889	4.009	1.244	0.326	0.956		0.34	0	0	0	0
LSR	0.019	0.087	0.02	-0.008	0.061	0.179		0	0	0	0
CT_L	0.322	0.908	0.679	0.064	0	0	0		0.39	-0.17	0.22
CT_F	0.382	1.15	0.302	0.284	0	0	0	0.443		-0.13	0.15
FECS	-0.039	-0.094	-0.022	-0.006	0	0	0	-0.057	-0.053		0.6
FECN	0.036	0.086	0.069	-0.001	0	0	0	0.052	0.044	0.051	

Residual Covariances (below) and correlations (above)

	8 WK	**SWT**	**MD**	**FD**	**MAT**	**MS**	**LSR**	**CT_L**	**CT_F**	**FECS**	**FECN**
8 WK		0.08	0.03	0.26	0	0.11	0.04	0.4	0.3	-0.01	-0.09
SWT	0.4		0.58	0.31	0.11	0.42	0.18	0.75	0.75	0	-0.12
MD	0.086	2.53		0.28	0.15	0.33	-0.12	0.3	0.3	-0.07	-0.13
FD	0.3	0.51	0.3		0.14	0.08	0.19	0.35	0.55	-0.1	-0.02
MAT	0	0.957	0.832	0.294		0.21	-0.14	0	0	0	0
MS	0.726	4.044	2.011	0.18	2.516		0.23	0	0	0	0
LSR	0.041	0.285	-0.117	0.073	-0.29	0.503		0	0	0	0
CT_L	1.117	3.028	0.772	0.34	0	0	0		0.7	0	-0.18
CT_F	1.01	3.65	0.931	0.645	0	0	0	1.996		0.01	-0.1
FECS	-0.015	0	-0.097	-0.052	0	0	0	0	0.015		0.23
FECN	-0.08	-0.154	-0.107	-0.006	0	0	0	-0.136	-0.091	0.093	

Appendix 2 Survey questionnaire of Housing at Lambing

Name	
Address	

Please indicate below the method of housing at lambing time you typically adopt for your performance recorded ewes…

All recorded ewes are housed for the duration of lambing	

All recorded ewes are lambed outdoors	

A combination of indoor and outdoor systems is used for all recorded ewes…

a) Some lamb indoors, some outdoors *(please give details about groups overleaf e.g. twins in, singles out, etc)*	
b) All are lambed outdoors during the day and indoors at night	
c) Other *(please give details overleaf)*	

Has the policy indicated above significantly changed in the time you have been performance recording?	**Y / N**

Please provide details of change including year it took place	

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