Table S1. Prices of feed ingredients in given months in France (€/t, including cost of transport to the feed factory) used in the four economic contexts of feed formulation

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Sep 2011 | Jun 2012 | Aug 2013 | Feb 2014 |
| Cereals |  |  |  |  |
|  Barley | 209 | 202 | 183 | 164 |
|  Maize grain | 212 | 221 | 203 | 169 |
|  Oats | 244 | 252 | 172 | 142 |
|  Sorghum grain | 210 | 212 | 182 | 175 |
|  Triticale | 207 | 215 | 192 | 172 |
|  Wheat | 209 | 225 | 192 | 184 |
| Maize co-products  |  |  |  |  |
|  DDGSa  | 246 | 299 | 268 | 292 |
|  Gluten feeda | 199 | 232 | 235 | 237 |
|  Gluten meal | 679 | 657 | 882 | 919 |
|  Wheat co-products  |  |  |  |  |
|  DDGSa | 241 | 324 | 344 | 329 |
|  Feed floura | 225 | 239 | 212 | 212 |
|  Gluten feeda | 184 | 204 | 203 | 225 |
|  Middlingsa | 161 | 187 | 181 | 180 |
|  Bran | 136 | 149 | 148 | 141 |
| Fats |  |  |  |  |
|  Crude palm oil | 826 | 916 | 701 | 705 |
|  Rapeseed oil | 1016 | 1033 | 852 | 778 |
|  Soya bean oil (Brazil) | 1001 | 1029 | 830 | 774 |
|  Sunflower oil | 1008 | 1002 | 855 | 698 |
|  Pig larda | - | 845 | 696 | 684 |
| Industrial amino acids |  |  |  |  |
|  DL-Methionine  | 3672 | 3322 | 3022 | 2822 |
|  L-Lysine  | 1972 | 1972 | 1422 | 1222 |
|  L-Threonine | 1902 | 1872 | 1772 | 1622 |
|  L-Tryptophane | 10022 | 8272 | 12022 | 12022 |
|  Valine | 12022 | 12022 | 12022 | 12022 |
| Minerals |  |  |  |  |
|  Calcium carbonate | 72 | 72 | 72 | 72 |
|  Dicalcium phosphate | 582 | 582 | 582 | 582 |
|  Monocalcium phosphate | 672 | 672 | 672 | 672 |
|  Sodium bicarbonate | 552 | 552 | 552 | 552 |
|  Sodium chloride | 112 | 112 | 112 | 112 |
| Oil seeds and protein crops |  |  |  |  |
|  Fava bean | 242 | 317 | 252 | 272 |
|  Rapeseed | 473 | 512 | 430 | 409 |
|  Soya bean, extruded | 460 | 519 | 512 | 466 |
|  Spring pea | 237 | 247 | 237 | 272 |
|  Sunflower grain | 451 | 497 | 419 | 346 |
| Oil meals |  |  |  |  |
|  Rapeseed meal | 211 | 293 | 254 | 314 |
|  Soya bean meal  | 325 | 438 | 461 | 500 |
|  Sunflower meal (not dehulled) | 156 | 228 | 210 | 204 |
|  Sunflower meal (United Kingdom) | 197 | 273 | 250 | 260 |
| Other co-products of plant origin |  |  |  |  |
|  Alfalfa, protein concentrate | 722 | 772 | 747 | 747 |
|  Molasses (beet, France)a | 210 | 217 | 247 | 247 |
|  Molasses (sugar cane, Pakistan)a | 227 | 222 | 242 | 234 |
|  Dehydrated sugar beet pulp  | 177 | 212 | 262 | 249 |
| Microbial phytase | 9522 | 9522 | 9522 | 9522 |
| Urea | 427 | 447 | 327 | 362 |
| Vitamins |  |  |  |  |
|  Pig | 522 | 522 | 522 | 522 |
|  Broiler | 2700 | 2700 | 2700 | 2700 |

afeedstuff classified as by-product

Table S2. Mean chemical and nutritional composition of feeds formulated using least-cost (LC) and multiobjective (MO) formulations in the limited ingredient availability (LIM) scenario

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Growing Pig | Finishing Pig | Starter Broiler | Growing Broiler | Finishing Broiler | Young Bull | Growing Pig | Finishing Pig | Starter Broiler | Growing Broiler | Finishing Broiler | Young Bull |
| Characteristic | LC | LC | LC | LC | LC | LC | MO | MO | MO | MO | MO | MO |
| Dry matter (%, DM) | 87.6 | 87.4 | - | - | - | 88.0 | 87.3 | 87.2 | - | - | - | 88.3 |
| MEa (MJ/kg) | - | - | 11.9 | 12.4 | 12.6 | - | - | - | 11.9 | 12.4 | 12.6 | - |
| NEb (MJ/kg) | 9.5 | 9.5 | - | - | - | 6.8 | 9.5 | 9.5 | - | - | - | 6.8 |
| PDIEc (g/kg DM)  | - | - | - | - | - | 125 | - | - | - | - | - | 126 |
| PDINd (g/kg DM) | - | - | - | - | - | 181 | - | - | - | - | - | 185 |
| Crude protein % | 15.0 | 13.5 | 21.5 | 19.5 | 17.5 | 26.0 | 15.0 | 13.5 | 21.5 | 19.5 | 17.5 | 26.0 |
| Fat % | 2.6 | 2.4 | 5.5 | 6.8 | 6.9 | 3.3 | 2.8 | 2.2 | 6.4 | 7.4 | 8.3 | 2.9 |
| Crude fibre % | 4.8 | 4.6 | - | - | - | - | 4.6 | 4.3 | - | - | - | - |
| Calcium % | 0.7 | 0.6 | 0.9 | 0.7 | 0.6 | - | 0.7 | 0.6 | 0.9 | 0.7 | 0.6 | - |
| Total phosphorus % | 0.5 | 0.4 | 0.7 | 0.6 | 0.5 | 0.7 | 0.5 | 0.4 | 0.7 | 0.6 | 0.5 | 0.8 |
| Available phosphorus % | 0.3 | 0.2 | 0.4 | 0.4 | 0.3 | - | 0.3 | 0.3 | 0.4 | 0.4 | 0.3 | - |
| Chlorine % | 0.4 | 0.4 | 0.2 | 0.3 | 0.3 | - | 0.4 | 0.4 | 0.2 | 0.3 | 0.3 | - |
| Sodium % | 0.2 | 0.2 | 0.1 | 0.2 | 0.1 | - | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | - |
| dLyse % | 0.8 | 0.7 | 1.2 | 1.1 | 0.9 | - | 0.8 | 0.7 | 1.2 | 1.0 | 0.9 | - |
| dMete % | 0.2 | 0.2 | 0.5 | 0.5 | 0.5 | - | 0.2 | 0.2 | 0.5 | 0.5 | 0.4 | - |
| dTSAA % | 0.5 | 0.5 | 0.8 | 0.8 | 0.7 | - | 0.5 | 0.4 | 0.9 | 0.8 | 0.7 | - |
| dThre | 0.5 | 0.4 | 0.7 | 0.7 | 0.6 | - | 0.5 | 0.4 | 0.8 | 0.7 | 0.6 | - |
| dTrpe | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | - | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | - |
| dVale | 0.6 | 0.5 | 0.9 | 0.8 | 0.7 | - | 0.6 | 0.5 | 0.9 | 0.8 | 0.7 | - |
| dArge | - | - | 1.3 | 1.1 | 1.0 | - | - | - | 1.3 | 1.1 | 1.0 | - |

aME: metabolisable energy

bNE: net energy

cPDIE: protein digested in the small intestine supplied by rumen undegraded dietary protein and microbial protein from rumen-fermented organic matter

dPDIN: protein digested in the small intestine supplied by rumen undegraded dietary protein and microbial protein from rumen degraded nitrogen

edLys, dMet, dTSAA, dThr, dTrp, dVal, dArg: digestible lysine, methionine, total sulphur amino acid, threonine, tryptophan, valine, and arginine, respectively.

Table S3. Mean chemical and nutritional composition of feeds formulated using the least-cost (LC) and multi-objective (MO) formulations in the non-limited ingredient availability (NLIM) scenario

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Growing Pig | Finishing Pig | Starter Broiler | Growing Broiler | Finishing Broiler | Young Bull | Growing Pig | Finishing Pig | Starter Broiler | Growing Broiler | Finishing Broiler | Young Bull |
| Characteristic | LC | LC | LC | LC | LC | LC | MO | MO | MO | MO | MO | MO |
| Dry matter (%, DM) | 87.5 | 87.3 | - | - | - | 88.0 | 87.1 | 87.2 | - | - | - | 88.0 |
| MEa (MJ/kg) | - | - | 11.9 | 12.4 | 12.6 | - | - | - | 11.9 | 12.4 | 12.6 | - |
| NEb (MJ/kg) | 9.5 | 9.5 | - | - | - | 6.8 | 9.5 | 9.5 | - | - | - | 6.8 |
| PDIEc (g/kg DM)  | - | - | - | - | - | 125 | - | - | - | - | - | 125 |
| PDINd (g/kg DM) | - | - | - | - | - | 181 | - | - | - | - | - | 178 |
| Crude protein % | 15.0 | 13.5 | 21.5 | 19.5 | 17.5 | 26.0 | 15.0 | 13.5 | 21.5 | 19.5 | 17.5 | 26.0 |
| Fat % | 2.3 | 2.4 | 4.4 | 5.9 | 6.8 | 3.6 | 2.4 | 2.5 | 5.8 | 7.2 | 7.9 | 3.2 |
| Crude fibre % | 5.0 | 4.9 | - | - | - | - | 4.4 | 4.2 | - | - | - | - |
| Calcium % | 0.6 | 0.6 | 0.9 | 0.7 | 0.6 | - | 0.6 | 0.7 | 0.9 | 0.7 | 0.6 | - |
| Total phosphorus % | 0.5 | 0.4 | 0.6 | 0.6 | 0.5 | 0.8 | 0.5 | 0.4 | 0.7 | 0.6 | 0.5 | 0.8 |
| Available phosphorus % | 0.3 | 0.2 | 0.4 | 0.4 | 0.3 | - | 0.3 | 0.3 | 0.4 | 0.4 | 0.3 | - |
| Chlorine % | 0.4 | 0.4 | 0.2 | 0.3 | 0.3 | - | 0.3 | 0.4 | 0.2 | 0.3 | 0.3 | - |
| Sodium % | 0.1 | 0.2 | 0.2 | 0.1 | 0.2 | - | 0.1 | 0.2 | 0.2 | 0.1 | 0.2 | - |
| dLyse % | 0.8 | 0.7 | 1.1 | 1.1 | 0.9 | - | 0.8 | 0.7 | 1.2 | 1.1 | 0.9 | - |
| dMete % | 0.3 | 0.2 | 0.5 | 0.5 | 0.5 | - | 0.3 | 0.2 | 0.5 | 0.5 | 0.5 | - |
| dTSAA % | 0.5 | 0.4 | 0.8 | 0.8 | 0.7 | - | 0.5 | 0.4 | 0.9 | 0.8 | 0.7 | - |
| dThre | 0.5 | 0.4 | 0.7 | 0.7 | 0.6 | - | 0.5 | 0.4 | 0.8 | 0.7 | 0.6 | - |
| dTrpe | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | - | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | - |
| dVale | 0.6 | 0.5 | 0.9 | 0.8 | 0.7 | - | 0.6 | 0.5 | 0.9 | 0.8 | 0.7 | - |
| dArge | - | - | 1.3 | 1.1 | 1.0 | - | - | - | 1.3 | 1.2 | 1.0 | - |

aME: metabolisable energy

bNE: net energy

cPDIE: protein digested in the small intestine supplied by rumen undegraded dietary protein and microbial protein from rumen-fermented organic matter

dPDIN: protein digested in the small intestine supplied by rumen undegraded dietary protein and microbial protein from rumen degraded nitrogen

edLys, dMet, dTSAA, dThr, dTrp, dVal, dArg: digestible lysine, methionine, total sulphur amino acid, threonine, tryptophan, valine, and arginine, respectively.

**Materials and Methods for sensitivity analysis**

In order to investigate the possible effects of the values of weighting factors on the outputs of the multiobjective feed formulation problem, we performed sensitivity analysis (SA) of PD, CC, AC, EU, NRE, LO and feed price to the weighting factors of the objective function.

For this purpose, we propose an objective function $MOg$ which is a generalisation of equation (6). $MOg$ allows variation of the weighting factors while ensuring that the sum of the weighting factors which apply on environmental impacts sum up to 1.

|  |  |
| --- | --- |
| $$min MOg=\left(1-α\right)×\left(\frac{Cost}{Cost^{ref}}\right)+α×\left(\frac{1}{δ\_{PD}+δ\_{CC}+δ\_{NRE}+δ\_{LO}}\right)×\left(δ\_{PD}\frac{LCA\_{PD}}{LCA\_{PD}^{ref}}+δ\_{CC}\frac{LCA\_{CC}}{LCA\_{CC}^{ref}}+δ\_{NRE}\frac{LCA\_{NRE}}{LCA\_{NRE}^{ref}}+δ\_{LO}\frac{LCA\_{LO}}{LCA\_{LO}^{ref}}\right)$$ | (9) |
|  |  |

Where $α$, $δ\_{PD}$, $δ\_{CC}$, $δ\_{NRE}$, $δ\_{LO}$ are weighting factors. The link between equations (6) and (9) is made by the transformation of variables that apply on weighting factors, e.g. for PD:

|  |  |
| --- | --- |
| $$β\_{PD}=^{δ\_{PD}}/\_{\left(δ\_{PD}+δ\_{CC}+δ\_{NRE}+δ\_{LO}\right)}$$ | (10) |

For an illustrative purpose, the sensitivity of PD, CC, AC, EU, NRE, LO to $α$, $δ\_{PD}$, $δ\_{CC}$, $δ\_{NRE}$, $δ\_{LO}$ was only calculated for pig feeds. Sensitivity indices were produced for each of the 4 economic contexts previously described.

The Sobol method for SA was chosen as the mostly recommended method to perform global SA, i.e. SA which calculates sensitivity indices for the whole range of variation of the parameters and accounting for the effects of interactions between parameters (1). Sobol is a variance-based method, which means that it assesses the contribution of parameters variance to the variance of model output (2). For a model output $Y=f(X)$ (where $f(.)$ is the model function, and $X=(X\_{1},…, X\_{K})$ the vector of the total number of parameters), the total variance of $f\left(X\right)$ can be decomposed as:

|  |  |
| --- | --- |
| $$Var\left(Y\right)=\sum\_{i=1}^{K}V\_{i}(Y)+\sum\_{i<j}^{K}V\_{ij}(Y)+…+V\_{12…K}(Y)$$ | (11) |

where $V\_{i}\left(Y\right)=Var(E\left(X\_{i}\right))$,$ V\_{ij}\left(Y\right)=Var(E\left(X\_{i},X\_{j}\right))-V\_{i}\left(Y\right)-V\_{j}(Y)$,...

Sobol first-order indices are defined as:

|  |  |
| --- | --- |
| $$S\_{i\_{1},…,i\_{s}}(Y)={V\_{i\_{1},…,i\_{s}}(Y)}/{Var(Y)}$$ | (12) |

The term $S\_{i\_{1},…,i\_{s}}(Y)$ equals the proportion of total variance of output $Y$ which is due to the combination of parameters ($X\_{i\_{1}},…, X\_{i\_{s}})$. The first-order index $S\_{i}$ describes the effect of parameter $X\_{i}$ on model output. The total-order indices describe effects on model output due to both parameters and interactions between parameters (3). First- and total-order indices are calculated for each output of interest. The experimental design was built using Latin hypercube sampling (LHS) with 100000 values taken from a uniform distribution [0, 1] for each parameter. Sobol indices were computed with the function soboljansen of the R package sensitivity (4,5).

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