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47. Multi-objective formulation is an efficient methodology to reduce environmental impacts of pig feeds

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ABSTRACT

The production of pig feeds has a major contribution to climate change, energy use and land occupation impacts of the animal product. Nonetheless, the traditional least-cost (LC) feed formulation methods minimize the cost of the feed mix, without consideration of its environmental impacts. The objective of this study was to estimate the potential mitigation of environmental impacts calculated by Life Cycle Assessment through a multi-objective formulation of pig feeds, in the French context. The linear programming problem built searches the best feed formula under nutritional constraints with a multi-objective function including an economic price index (price of the feed mix relative to LC formulation) and an environmental impacts index (environmental impacts relative to LC formulation). A weighting coefficient between price and environment (α) ranging from 0 to 1 was included. Growing and finishing feeds were formulated with two scenarios of feed ingredients availability (current limited LIM, increased NLIM) and 4 scenarios of feed ingredient prices. When increasing α from 0 to 0.5, the environmental indexes of the growing and finishing feeds dropped down to -10% in LIM and down to -17 to -20% in NLIM scenario, respectively. Concomitantly, the average feed price increased by 1.5% in LIM and 1.7% in NLIM. For α higher than 0.5, the environmental index was almost no further reduced. At $\alpha=0.5$, all the impacts considered were reduced relatively to LIM-LC, excepted for land occupation in NLIM. The low-impact feeds incorporated higher proportions of pea and wheat middlings and lower proportions of meals (rapeseed and sunflower) than LC formulated feeds. The multi-objective formulation of pig feeds is an efficient methodology to find low-impact feeds according to a given economic scenario. Improving the availability of some feed ingredients (pea, co-products of wheat...) at the territory level would allow (at same feed's nutritional composition) further reduction of pig feeds impacts relatively to the current French context. Multi-objective formulation can provide a decision support tool to the feed industry to produce low-impact feeds for the pig production chain.

Keywords: optimization, feed formulas, linear programming, pig feeds.

1. Introduction

Pig production systems (PPS) are facing societal, environmental and economic challenges all around the world. Animal production is expected to increase in the following years to feed the raising human demand for animal products (FAO, 2011). PPS should also reduce their environmental burden. They are associated various environmental impacts like climate change, land use, and eutrophication particularly in territories with high concentrations of livestock (North West France, Netherlands...). The rising of the feed ingredients prices (cereals and meals from oilseeds and protein crops) and the volatility of the animal products prices also reduce the stability and the average level of the gross margin of pig producers (EC, 2013).

In farrow-to-finish PPS, feeds account for 60% to 70% of the feeding cost and the production of feeds has a major contribution to climate change (55%-75%), energy use (70%-90%) and land occupation (85%-100%) impacts of the animal product (Basset-Mens and van der Werf, 2005; Dourmad *et al.*, 2014). Both feeds' cost and environmental impacts are highly determined by their composition in feed ingredients. Some of them, like soybean meal, account for more than 10% of the feed composition and are characterized by relatively high price and impacts (Wilfart *et al.*, 2016). Some other feed ingredients are incorporated into small amounts into feeds but have high environmental impacts per kilogram, e.g. feed-use amino acids and monocalcium phosphate (Garcia-Launay *et al.*, 2014). Therefore, there is possibly a great potential to reduce the environmental impacts of animal products through the formulation of low-impact feeds (Nguyen *et al.*, 2012).

Nonetheless, the traditional least-cost (LC) feed formulation method minimizes the cost of the feed mix, without consideration of its environmental impacts. LC formulation incorporates the feed ingredients to meet nutritional requirements according to production objectives, while minimizing the cost of the feed mix, using a linear programming model which calculates the feed cost as the objective function. However, the maximal technical performance does not necessarily correspond to the

economic and/or environmental optimum (Morel *et al.*, 2012; Pomar *et al.*, 2007). Therefore formulating low-impact feeds requires an alternative approach to LC. Castrodeza *et al.* (2005) developed a multiple goal programming model accounting for the feed cost and the excess of feed contents in amino acids and phosphorus, which does not consider the environmental impacts of the feed ingredients themselves. Nguyen *et al.* (2012) formulated low-impact feeds for poultry feeds under constraints of feed's climate change and eutrophication impacts with the cost being the objective function. They highlighted that accounting for only two impacts may lead to pollution transfer. Therefore, there is no reliable and simple feed formulation method available for feed manufacturers that aim at reducing both the feed cost and its environmental impacts. The objectives of this study were to develop a multi-objective formulation method of pig feeds relying on environmental impacts of feed ingredients calculated by Life Cycle Assessment (LCA), and to illustrate its potential to mitigate the environmental impacts of feeds for fattening pigs in the French context.

2. Methods

Table 1. List and description of the variables, vectors and matrixes inputs of the feed formulation problem.

	Inputs of the problem	Description
(1)	$\begin{bmatrix} Nut_{11} & \cdots & Nut_{p1} \\ \vdots & \ddots & \vdots \\ Nut_{1n} & \cdots & Nut_{pn} \end{bmatrix}$	Matrix of the nutrients composition of each feed ingredient, Nut_{ij} being the content of nutrient j in feed ingredient i .
(2)	$\begin{bmatrix} LCA_{11} & \cdots & LCA_{q1} \\ \vdots & \ddots & \vdots \\ LCA_{1n} & \cdots & LCA_{qn} \end{bmatrix}$	Matrix of the environmental impacts of each feed ingredient, LCA_{ik} being the k^{th} environmental impact of feed ingredient i .
(3)	$\begin{bmatrix} MinNut_1 \\ \vdots \\ MinNut_p \end{bmatrix} \text{ and } \begin{bmatrix} MaxNut_1 \\ \vdots \\ MaxNut_p \end{bmatrix}$	Vectors of the nutrient requirements and of the maximum nutrients contents of the feed, defined in accordance with the animal performance objective.
(4)	$\begin{bmatrix} MinRate_1 \\ \vdots \\ MinRate_n \end{bmatrix} \text{ and } \begin{bmatrix} MaxRate_1 \\ \vdots \\ MaxRate_n \end{bmatrix}$	Vectors of the minimum and maximum incorporation rates for each feed ingredient i .
(5)	$\begin{bmatrix} 105\% \times FLCA_{q-1ref} \\ \vdots \\ 105\% \times FLCA_{qref} \end{bmatrix}$	Vector of the maximum values for the environmental impacts not included in the MO function (eutrophication and acidification).
(6)	$[Cost_1 \dots Cost_n]$	Vector of cost of each feed ingredient i

Multi-objective optimization of the feed formulas with both economic and environmental indicators has been chosen in order to avoid pollution transfer and to produce formulas consistent with the current praxis of the feed manufacturers. The multi-objective formulation method calculates the nutritional contents, the cost and the LCA environmental impacts of the considered feed from the characteristics of each feed ingredient (FI) and the associated incorporation rates.

Feed ingredients characteristics

FI impacts came from the ECOALIM dataset of the AGRIBALYSE® database (Wilfart *et al.*, 2016) and included phosphorus demand (PD, in kg P/kg of FI), ILCD climate change including land use change (CC, in kgCO₂-eq/kg), ILCD acidification (AC, in molcH⁺-eq/kg), CML eutrophication (EU, in kgPO₄₃-/kg), CED 1.8 non-renewable energy demand (NRE, in MJ/kg), and CML land occupation (in m².year/kg). The impacts of the feed ingredients transport from the storage

organization to the feed factory were added with background data from Ecovinvent v3.1. attributional database (Weidema *et al.*, 2013) considering average distances of pig production in Brittany, North-West of France to the main areas of cereals production, to the harbors of imported meals and the distances to mills and starch manufactures. Nutritional composition of the feed ingredients came from Sauvant *et al.* (2004) excepted for few co-products for which data were provided by R&D institutes. All the impacts were considered at the entry of the feed factory for an application in feed manufacturing.

Table 2. List and description of the variables, vectors and matrixes outputs of the feed formulation problem.

	Outputs of the problem	Description
(7)	$\begin{bmatrix} Rate_1 \\ \vdots \\ Rate_n \end{bmatrix}$ and $\begin{bmatrix} Rate_{1ref} \\ \vdots \\ Rate_{nref} \end{bmatrix}$	Decision vectors where each $Rate_{iref}$ and $Rate_i$ corresponds to the incorporation rate for the feed ingredient i in the reference feed and MO optimized feed
(8)	$\begin{bmatrix} FNut_1 \\ \vdots \\ FNut_p \end{bmatrix}$ and $\begin{bmatrix} FNut_{1ref} \\ \vdots \\ FNut_{pref} \end{bmatrix}$	Vectors of the nutrient contents of the feed formula where each $FNut_{jref}$ is the j^{th} nutrient content of the feed after LC formulation and $FNut_j$ is the j^{th} nutrient content of the feed after MO formulation.
(9)	$[FLCA_{1ref} \dots FLCA_{qref}]$	Vector of the environmental impacts of the reference formula produced after LC formulation where $FLCA_{kref}$ is the k^{th} environmental impact of the reference formula
(10)	$[FLCA_1 \dots FLCA_q]$	Vector of the environmental impacts of the formula produced after MO formulation where $FLCA_k$ is the k^{th} environmental impact of the formula

The multi-objective feed formulation problem

Like in the LC traditional formulation method, the multi-objective formulation method developed was based on linear programming (Figures 1 and 2). The incorporation rates of each available feed ingredient were determined under a series of linear constraints, while minimizing the objective function. The list and description of variables, vectors and matrixes utilized for the feed formulation problem is available in Tables 1 and 2. The method was developed in two steps: first one to produce a reference formula through LC formulation (Figure 1) and second step searching for the solution of the multi-objective optimization problem (Figure 2).

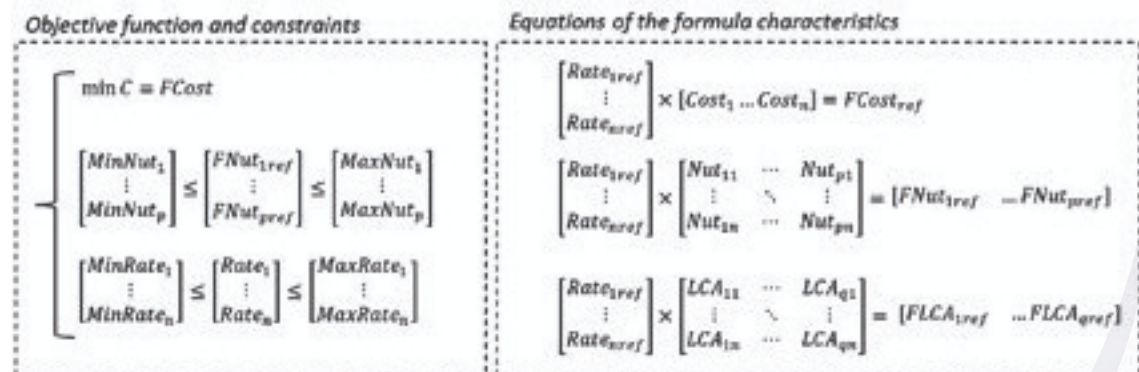


Figure 1. First-step of the multi-objective optimization problem involving traditional least-cost formulation minimizing function C to define a reference formula, and a second step with optimization of the multi-objective (MO) function.

First step corresponds to a traditional LC formulation which aims at producing a reference formula. The objective function is the feed cost which is calculated as the sum of the feed ingredients costs (6) multiplied by their respective incorporation rates. The optimization algorithm searches for

incorporation rates (7) that minimize the objective function while covering the nutritional requirements (3) of the pig and under constraints of incorporation rates (4) for each feed ingredient. Feeds are formulated while ensuring minimum nutrient contents, in order to cover the animal requirements in net energy and amino acids according to the performance objective. Minimum limits for standardized ileal digestible amino acids were calculated according to the regulation on pig feed protein content (CORPEN, 2003) and ideal amino acid profiles from van Milgen *et al.* (2008). Minimum and maximum values of feed ingredients incorporation rates have been established to account for both the availability of each feed ingredient on the market and the technological constraints of the feed fabrication. From the formula produced during this first step, the reference values for feed cost, LCA environmental impacts (9), and nutrient contents are calculated (8).

Multi-objective function

$$\min MOF = (1 - \alpha) \underbrace{\frac{FCost}{FCost_{ref}}}_{\text{Price index}} + \alpha \underbrace{\left(\frac{2\beta \times FLCA_1}{FLCA_{1ref}} + \frac{\beta \times FLCA_2}{FLCA_{2ref}} + \frac{\beta \times FLCA_3}{FLCA_{3ref}} + \frac{\beta \times FLCA_4}{FLCA_{4ref}} \right)}_{\text{Environmental impacts index}}$$

Constraints

$$\begin{cases} \begin{bmatrix} MinNut_1 \\ \vdots \\ MinNut_p \end{bmatrix} \leq \begin{bmatrix} FNut_1 \\ \vdots \\ FNut_p \end{bmatrix} \leq \begin{bmatrix} MaxNut_1 \\ \vdots \\ MaxNut_p \end{bmatrix} \\ \begin{bmatrix} MinRate_1 \\ \vdots \\ MinRate_n \end{bmatrix} \leq \begin{bmatrix} Rate_1 \\ \vdots \\ Rate_n \end{bmatrix} \leq \begin{bmatrix} MaxRate_1 \\ \vdots \\ MaxRate_n \end{bmatrix} \\ \begin{bmatrix} FLCA_{q-1} \\ \vdots \\ FLCA_q \end{bmatrix} \leq \begin{bmatrix} 105\% \times FLCA_{q-1ref} \\ \vdots \\ 105\% \times FLCA_{qref} \end{bmatrix} \end{cases}$$

Equations of the formula characteristics

$$\begin{cases} \begin{bmatrix} Rate_1 \\ \vdots \\ Rate_n \end{bmatrix} \times [Cost_1 \dots Cost_n] = FCost \\ \begin{bmatrix} Rate_1 \\ \vdots \\ Rate_n \end{bmatrix} \times \begin{bmatrix} Nut_{11} & \dots & Nut_{p1} \\ \vdots & \ddots & \vdots \\ Nut_{1n} & \dots & Nut_{pn} \end{bmatrix} = [FNut_1 \dots FNut_p] \\ \begin{bmatrix} Rate_1 \\ \vdots \\ Rate_n \end{bmatrix} \times \begin{bmatrix} LCA_{11} & \dots & LCA_{q1} \\ \vdots & \ddots & \vdots \\ LCA_{1n} & \dots & LCA_{qn} \end{bmatrix} = [FLCA_1 \dots FLCA_q] \end{cases}$$

Figure 2. Second step of the multi-objective optimization problem with optimization of the multi-objective (MO) function.

The second step of the feed formulation problem utilizes the constraints of the LC formulation and calculates a multi-objective (MO) function including cost and environmental impacts criteria (Figure 2). All the criteria included in the MO function are normalized by their reference value calculated from the LC formulation. The MO function includes a price index which is the normalized feed cost and an environmental impacts index which comprises four normalized environmental impacts. Global impacts for which feed has a major contribution have been selected to be included in the MO function: climate change, phosphorus demand, non-renewable energy demand, and land occupation (Basset-Mens and van der Werf, 2005; Dourmad *et al.*, 2014). Eutrophication and acidification have been also included in the problem considering the algal bloom eutrophication occurring in several costs of Brittany, the main area for pig production in France. Both have been utilized as constraints (5) of the feed formulation problem, their value being limited to 105% of their reference value from the LC formulation (Figure 1). The MO function also includes two weighting factors, α and β . The α factor corresponds to the weight, ranging from 0 to 1, for the environmental impacts index, $1 - \alpha$ being the complementary weight on the price index. The β factor, which equals 0.2 in our case, manages the weighting between the four environmental impacts included. A double 2β has been allocated to the climate change impact considering the strong international efforts that are made to mitigate this impact (Gerber *et al.*, 2013). All the β factors included in the environmental impacts index sum up to 1. Therefore the MO function while moving the α factor from 0 to 1 allows investigating the trade-off between economic and environmental objectives. The optimization algorithm searches for

incorporation rates that minimize the MO function while respecting the constraints of the LC formulation and under constraints (3) (4) on local environmental impacts increase (5).

Simulation of scenarii

The MO method was tested for the formulation of growing and finishing feeds for fattening pigs considering that fattening has the major contribution in pig production to the feeding cost and to the environmental impacts (Garcia-Launay *et al.* 2014). To investigate the ability of the MO method developed to formulate low-impact feeds, we defined several scenarii to account for the variability of the situations encountered in France. Two scenarios of feed ingredients availability (to define the vector (4) and 4 scenarios of feed ingredients prices (6) have been developed.

The current limited (LIM) and increased (NLIM) availability scenarii have been developed from expert knowledge and correspond respectively to the current situation in France and to an increased potential availability of some feed ingredients such as spring peas, faba beans ... The 4 economic scenarii were constructed in order to cover a range of contrasted situations and correspond respectively to the market feed ingredients prices in September 2011, June 2012, August 2013 and February 2014. These four periods have been selected because they were characterized by varying prices of soft wheat, maize grain and soybean meal which resulted in contrasted soybean meal/soft wheat and maize grain / soft wheat ratios of prices. Costs were obtained from La Dépêche Commerciale (2011, 2012, 2013, and 2014) market newspaper and from Arvalis R&D institute.

Feeds of the scenarii limited availability and least-cost formulation (LIM-LC), limited availability and MO formulation (LIM-MO), and increased availability with MO formulation (NLIM-MO) were evaluated. Feeds were formulated using OpenSolver for Excel (Mason and Dunning, 2010), open source software which performs optimization of linear programming models using branch and bound, for problems with a large number of variables and constraints.

3. Results

Results provided are average values over the 4 economic scenarios.

Feed formulas

Average feed formulas for the finishing feed are provided in Figure 3. Proportion of cereals and oilmeals in feed formulas decreased from the LIM-LC to the NLIM-MO scenario while proportions of coproducts of wheat and of oilseeds and protein crops increased. Proportion of coproducts of wheat and of oilseeds and protein crops increased from LIM-LC to LIM-MO formulation because these feed ingredients were characterized by lower environmental impacts than cereals and oilmeals. Proportion of coproducts of wheat, and of oilseeds and protein crops amplified between LIM and NLIM in MO formulation because of the improved availability of coproducts and protein crops like wheat middlings, wheat feed flour and spring peas in the NLIM scenario. The same statement was also observed for growing feeds.

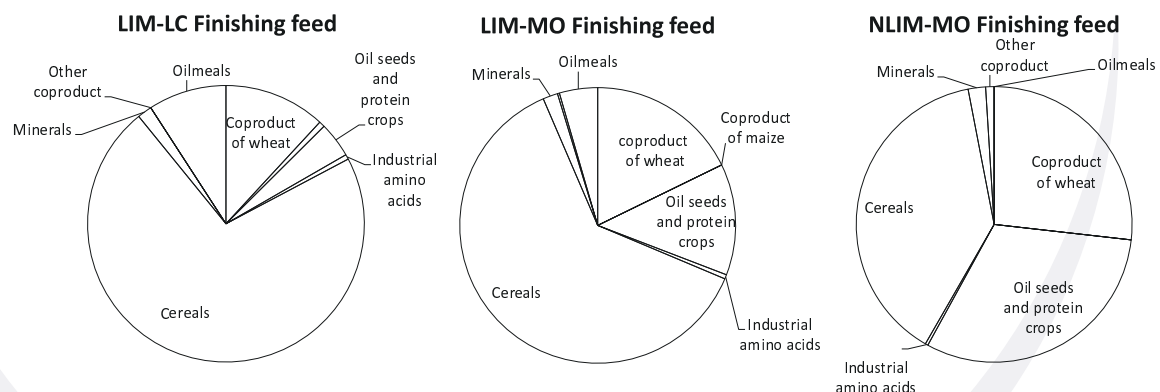


Figure 3. Average feed formulas over the 4 economic scenarii, obtained for LIM-LC (limited availability of feed ingredients and least-cost formulation), LIM-MO (limited availability and multiobjective formulation), and NLIM-MO (increased availability and multiobjective formulation).

Variation of feed cost and environmental impacts with MO formulation

Figure 4 shows the variations of the average price index and the average environmental impacts index (over the 4 economic scenario) of the feed formulas when α varies from 0 to 1. When $\alpha=0$ the price index and environmental index were close to 1 because it corresponds to LC formulation. When α varied from 0 to 0.5 the price index of the feeds in NLIM was increased by 2% while the environmental impact index was reduced by 17-20%. When further increasing α up to 1, the price index reached +5-6% while the environmental impacts index remained almost stable. The variations were similar for the LIM scenario but to a lower extent. This relationship between price and environmental impacts indexes shows that in our context it was not advisable to increase the value of α to more than 0.5 because no further mitigation of impact could be expected.

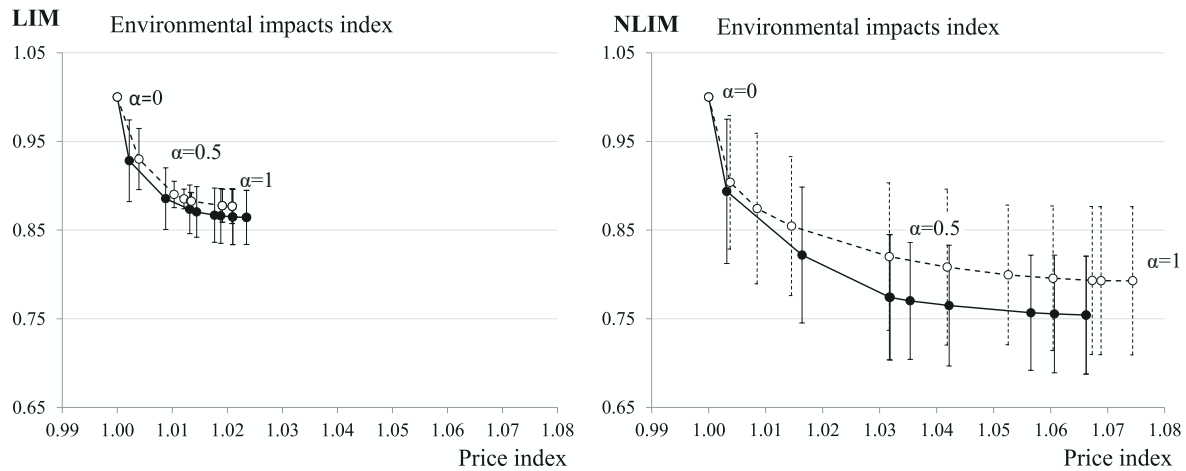


Figure 4. Variation of average environmental and price indexes in LIM and NLIM scenarios when formulating growing (●) and finishing (○) feeds with α ranging from 0 to 1.

Consequently, Table 3 provides the average prices and the average environmental impacts of the feed mix (40% growing / 60% finishing) formulated at $\alpha=0.5$. Relatively to LIM-LC, LIM-MO reduced all the environmental impacts included in the MO function as well as eutrophication and acidification impacts, while slightly increasing feed price (+1%). Relatively to LIM-MO, NLIM-MO further decreased all the environmental impacts excepted land occupation while further increasing feed price (+1%).

Table 3: Average price and environmental impacts (\pm s.d. | % relatively to LIM-LC) of 1t of feed mix (40% growing and 60% finishing) produced, for the reference scenario (LIM-LC) and the LIM-MO and NLIM-MO scenario at $\alpha = 0.5$.

Feed price and environmental impacts	LIM-LC	LIM-MO $\alpha = 0.5$	NLIM-MO $\alpha = 0.5$
Feed price (€)	216 \pm 12.4	219 \pm 12.2 +1.0%	222 \pm 8.4 +2.7%
Phosphorus Demand (kg P)	3.4 \pm 0.36	3.2 \pm 0.15 -6%	2.7 \pm 0.15 -21%
Non-renewable Energy (MJ)	5150 \pm 568.7	4442 \pm 351.2 -14%	3899 \pm 290.5 -24%
Climate Change (kgCO ₂ -eq)	499 \pm 18.2	426 \pm 4.6 -15%	337 \pm 11.5 -32%
Land Occupation (m ² .year)	1418 \pm 59.5	1238 \pm 13.1 -13%	1325 \pm 61.8 -6%
Acidification (mol H ⁺)	9.7 \pm 0.48	9.0 \pm 0.58 -7%	6.6 \pm 0.42 -32%
Eutrophication (kg PO ₄ ⁻)	3.6 \pm 0.05	3.2 \pm 0.02 -11%	2.9 \pm 0.09 -19%

4. Discussion

This paper proposes a novel methodology for feed formulation, which aims at integrating the environmental impacts calculated by LCA in the traditional least-cost formulation approach. The development of the multiobjective formulation method was made possible by the development of the ECOALIM dataset of the AGRIBALYSE® database which provides homogeneously developed and reliable environmental impacts (Wilfart et al., 2016). Indeed optimization is useful for decision support but may lead to inappropriate decisions if the model of calculation and the underlying data are not robust in the range of situations investigated.

In the scenarii illustrated, the reduction of impacts through multi-objective formulation was obtained by incorporating less oil meals and cereals and more coproducts and protein crops (especially spring peas). Indeed, coproducts are characterized by relatively low impacts mainly associated to economic allocation of impacts adopted in the ECOALIM dataset and spring peas have lower impacts than meals like soybean meal and rapeseed meal (Wilfart *et al.*, 2016). The reduction of impacts was also improved in the NLIM scenario relatively to the LIM scenario. This statement suggests that better balance among various crop productions would benefit to the environmental impacts of the whole pork chain.

The inclusion of two indexes (price and environmental impacts) into the objective function with weighting factors allows investigating the relationships between feed price and environmental impacts. It gives to the end-user an overview of the possible trade-off that he can make between price and environmental impacts. In our scenarii, the reduction of impacts is of interest for $\alpha=0.5$ with a very moderate additional price and anyone can simply identify that there is no extra reduction expected when further increasing α . Therefore the end-user can choose the appropriate weighting of the price and environmental impacts indexes. Additionally, the multiobjective formulation approach proposed relies on the traditional customary least-cost formulation method for its first step and is consistent with the current formulation constraints and practices. This approach provides feed formulas in accordance with the concerns of the potential end-users. Finally, the incorporation of 4 environmental impacts into the objective function limits the risk of pollution transfer. However, the behavior of the MO linear programming model was also characterized by a decrease of the environmental index for α between 0.5 and 1 that was associated to further reduction of climate change but with concomitant augmentation of land occupation. Indeed, the reduction of this index may be associated to reduction of some impacts and increase of some other ones. In our case climate change with a weight of 2β compensated for land occupation augmentation. This statement highlights how important is the choice of the weighting factors of such a methodology.

Various formulation methods have already been proposed so far to account for the environmental burden of pig production (Castrodeza et al., 2005; Pomar et al., 2007, Nguyen et al., 2012, Garcia-Launay *et al.*, 2014). Some of them focused on the reduction of the crude protein and phosphorus supplies to the animals that are involved in the ammonia, nitrous oxide, nitrates and phosphates emissions occurring on farm. To our best knowledge, Nguyen *et al.* (2012) are the only authors that already included environmental impacts calculated by LCA in their feed formulation problem, but only as constraints. The multiobjective formulation proposed in the present paper is in fact complementary with these previous studies. Indeed the previous formulation methods mostly included nutrients excreted as constraints in order to modify the on-farm emissions, whereas the present method mitigates the upstream impacts.

The feed formulas obtained with the multi-objective formulation must be further evaluated on the pig unit. Indeed, formulas including high levels of coproducts and/or newly available products (microalgae, ...) may affect the animal performance, with an indirect effect on the environmental impacts.

5. Conclusions

Multi-objective formulation of pig feeds appears a promising approach to reduce upstream environmental impacts related to pig production. It refreshes the traditional least-cost formulation method by providing a methodology more in accordance with the current animal production issues and challenges. It gives an example of decision support using LCA studies and highlights the necessary precision and reliability of life cycle inventories to put into practice mitigation options. On-going work on broiler feeds will allow investigating the genericity of the proposed methodology.

Further work will include global assessment at farm gate of the feed formulas obtained through MO formulation.

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