PRODUCTION PLANNING OF SUPPLY CHAINS IN THE PIG INDUSTRY BY A MIXED INTEGER LINEAR PROGRAMMING MODEL

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ABSTRACT

This paper presents the formulation of a mixed integer linear programming model with the aim to optimize the supply chain for the pigs farms sector according to the Spanish specialization farms. This model maximize the benefit depending the demand and costs givent for each period and farm types. The proposed model takes in consideration the costs associated to each type of farm involved in the process as well as transportation costs associated, because of the especialization process, finding the best transfers between each farm to another in terms of distance, animals to be transfered and trucks to be used. Also genotypes grouping for each set of farms and constraints between them like farming cycles, lactation periods an costs associated are taken into account. Lot creation to transfer piglets and the different methods to fill farms like continous or all-in-all-out filling makes this model to achive most of the particularities of the pig farming in Spain.

Keywords: Linear programming; supply chaing model; sow herd management; replacement; herd transport; herd optimization

1.- INTRODUCTION

Nowadays, pig production process has shifted from a family business to a larger production process in order to satisfy the specified demand of pigs. Hence, the development of pork production from insemination until they are sold or led to the slaughterhouse involves different phases within the supply chain in which, the specialization of each of these alow an higher efficiency in pig production.

In Spain, the cycle of pig production mainly goes through three phases. The first one, where the sows are inseminated in order to produce the maximum number of piglets. Each sow is inseminated during a certain number of times and finally, when the sow is not as productive as expected, is led to the slaughterhouse. The piglets resulting from insemination are sent to the rearing farms being feeded for a specific number of weeks. Then, and finally, piglets are transfered to the fattering farms with the aim to make them gaining weight also for a specific number of weeks until they are led to the slaughterhouse.

For each of these phases in the production process, a set of specialized farms are involved with characteristics according to the needs. Farms are not always located one each other, but they may be located in different places so transportation is needed (mainly trucks). Hence cost to transport piglets are important in the production process and may vary between the number of piglets and distance.

Specialized pigs farms by genotype can do the production efficient. Having different genotypes in a set of farms involves to have different periods to achieve pigs with the correct weight as well as feeding or medical treatments. Therefore in farms of each one of the three phases, specialization by genotype is given enabling mono or multi genotype farms configuration creating some constraints in transport.

To mantain the whole process efficient is primordial to ensure the demand at a minimum cost, keeping the capacity of farms in the optimal level, reducing transportation costs and keeping a stock at all times in each production stages that allow to meet the demand not only at present, future as well.

So far, investigations have been done to improve the production results of pig farms with acceptable results. Some of these studies use Markov chain and simulation (Kristensen 1998 and Plà, 2007). Other studies concluded that optimization methods can help to achieve this goal. Plà et al. (2008), proposes linear programming models to optimize the entire supply chain, taking into account the constraints of each of the three types of farms. Even to deal with uncertainty in sow farm's variables, a stochastic optimization model has been proposed at Mula et al. (2006) and Rodriguez et al. (2009).

The aim of this paper is to formulate a mixed integer linear programming model to optimize the supply chain in in the pig industry keeping in mind the genotypes and transportation constraints between the phases and farms, proposing the number of animals moved between farms for each period. Moveover, taking into account variables such as the farm's capacity, periods, statuses and each set of constraints, the model will seek the maximum benefeit for the whole system according to the present and future demand in each period of time. This model will use real and actual data sets in a givent period of time in order to check the validity of it.

2.- BASICS FOR THE DEVELOPMENT OF THE MODEL

2.1.- High level model structure

The goal of this model is to get the maximum benefit we can achieve by optimizing the farm's supply model. This benefit is givent by the sum of pork led to the slaughterhouse substracting the total pigs expenses in each of the farms and the transport cost incurred. Transportation between phases in farm pigs and to the slaughterhouse occurs every period of time, generally weeks. Therefore, the benefit will be the sum of all periods. In a high level view, the model structure will be as follows:

$$\max \sum_{t=1}^{T} \left(v[t] - (c^{I}[t] + c^{II}[t] + c^{III}[t]) \right)$$

where:
T: Time horizon in weeks
v[t]: Total weekly incomings less the cost transportation associated in t period
c[t]: Total cost of all set of farms in the week t
I: set of sow farms
II: set of rearing farms
III: set of fattering farms

Each of these elemens $v[t]$, $c^{I}[t]$, $c^{II}[t]$ and $c^{III}[t]$ are discussed in more detail in the next points and a submodel is created.

2.2.- Transport costs calculation

Transport is calculated according the number of trucks needed to bring pigs from one farm to another. This cost depends mainly on the distance between these farms in kilometers. The capacity of each truck is constrained about a number of pigs and the total weight per truck. The model developed takes in consideration that the number of pigs that a truck is allowed to transport depends of each production phase as the pig's weight is not the same.

For design reasons, the distance between farms is taken as the euclidean distance between one farm to another onetaking the coordenates of their position in format Universal Transverse Mercator (UTM). The calculation is as follows:

$$d(a,b) = \frac{\sqrt{(x_I - x_{II})^2 + (y_I - y_{II})^2}}{1000}$$

where:

x_I : x UTM coordinate for the *'from'* farm

y_I : y UTM coordinate for the *'from'* farm

x_{II} : x UTM coordinate for the '*to'* farm or slaughterhouse

y_{II} : y UTM coordinate for the '*to'* farm or slaughterhouse

Since there is three types of farms, two pigs movements will be done between them. It seems fair, then, the transportation costs are added in rearing and fattering farms. Transportation between fattering farms to the slaughterhouse are added when the incomings are calculated , in $v[t]$.

Finally, in sow farms, transportation cost from the farm to slaughterhouse as well as incoming will be calculated due the sows where the reproduction period has finished. This case only occurs when sows are not productive anymore because their capacity to get pregnant is over.

2.3.- Constraints by genotype and transfers between farms

This model takes into account three different genotypes but can be extended to more and its corresponding intersections. In this case, genotypes Duroc (DU), Pietrain (PI) and Landrace (LA) are named. The crossing will result in concrete DUxLD, LDxPI, DUxLDxPI.

Each sow farm can produce one or more types of piglets according their genotype but transfers to rearing and fattering farms some genotypes must be grouped. The following table shows what percentage breeds can be grouped or not for each combination. These will be those that will be considered in implementing the model.

		Genotypes allowed					
	%	Du	DuxLD	LD	LDxPi	Pi	DuxLDxPi
Genotype	Du	1	1	0	0	0	1
	DuxLD	1	1	0	0	0	0
	LD	0	0	0,66	0	0	0,34
	LDxPi	0	0	0	1	0	1
	Pi	0	0	0	0	0,66	0,34
	DuxLDxPi	0	0	0	0	0	1

Table 1*. % Maximum animals of a certain genotype that can be used to produce the same or cross breeds.*

In addition, transfers between farms may occur in two ways according to the criteria of each farmer. First, piglets can be transferred to a specific farm continously, once per cycle (generally week). Another way is the "all in, all out" method, which lots are created of animals from different farms and the destination farm is enterely filled and stay in the farm for a certain number of cycles, and at the end, the animals are transferred in another farm or to the slaughterhouse.

To solve this case, each farm is marked using a binary variable to set up in which cycle the animals can be tranferred. The following table shows an example where “1” means that animals can be transferred in the cycle and “0” not.

Farm	Cycle #							
	1	2	3	4	5	6	7	8
All in All out in Cycle #1	1	0	0	0	0	0	0	0
Continuous in each cycle	1	1	1	1	1	1	1	1

Table 2. Setting up transfers between different types of farms

2.4.- Model for sow farms: $c^I[t]$

Sow’s farms submodel is created mainly by three cost elements. According to the order of appareance in the model, the total cost of sows is calculated according the stock in each sow state S in each farm. Secondly, the total cost for each farm regarding the piglet’s stock on every period of lactation is also included. Finally it is calculated the transporting costs of the sows to the slaughterhouse which are no longer expected to be inseminated anymore (normally after eight births). Note that these last type of sows will generate incomings also calculated, but as this is a cost submodel where the expected value is positive, the incomings are calculated in negative. Therefore:

$$\sum_{t=1}^{T} c^I[t] = \sum_{n'=1}^{N_I}\left(\overbrace{\sum_{i\in S} c_i^{n'} \frac{\pi_i^{n'}}{\tau_i^{n'}} \cdot T}^{sows} + \overbrace{\sum_{e=1}^{E_I}\sum_{t=1}^{T}\sum_{g=1}^{G} c_e^{n'} I^{n'}[e][t][g]}^{piglets} + \overbrace{\left(k^I \cdot c_v^{n^I} \cdot d(n',s) - \pi_8^{n'} \cdot p[t]\right)}^{transportation} \right)$$

subject to:

$$\frac{\pi_i^{n'}}{\tau_i^{n'}} - \sum_{i\in S} p_{ij}^{n'} \frac{\pi_i^{n'}}{\tau_i^{n'}} = 0 \qquad j \in S, n' \in I \qquad (1)$$

$$\sum_{i\in S} \pi_i^{n'} \le K^{n'} \qquad j \in S, n' \in I \qquad (2)$$

$$I^{n'}[e+1][t][g] \le I^{n'}[e][t-1][\mathrm{g}] \qquad e \in \{1,\ldots,E_I\}, t \in \{1,\ldots,T\}, g \in \{1,\ldots,G\}, n' \in I \qquad (3)$$

$$A^{n'}[t][g] \le I^{n'}[E_I][t][\mathrm{g}] \qquad t \in \{1,\ldots,T\}, g \in \{1,\ldots,G\}, n' \in I \qquad (4)$$

$$I^{n'}[1][t][g] \le \sum_{i\in S_g} \frac{\pi_i^{n'}}{\tau_i^{n'}} \cdot LS[g] \qquad t \in \{1,\ldots,T\}, g \in \{1,\ldots,G\}, n' \in I \qquad (5)$$

$$I^{n'}[e][0][g] = I_e^{n'}[\mathrm{g}] \qquad e \in \{1,\ldots,E_I\}, g \in \{1,\ldots,G\}, n' \in I \qquad (6)$$

$$\pi_8^{n'} <= k^I * kk^I \qquad n' \in I \qquad (7)$$

$$\pi_8^{n'} * qw^I <= k^I * kw^I \qquad n' \in I \qquad (8)$$

Where:
I: set of sow farms in phase I
E_I: number of weeks for the lactation period
T: time horizon in weeks
G: Genotypes

$I^{n'}[e][t][g]$: inventory of piglets of age $e \in E_I$ at week t by genotype $g \in G_I$ in the $n' \in I$ sow farm
$c_e^{n'}$: unitary cost per week related to piglets including feeding
$c_i^{n'}$: unitary cost per week related to sows including feeding
$c_v^{n''}$: unitary cost per week related to pig transport. Cost per truck
S: set of physiological states in which sow lifespan is divided.
$\pi_i^{n'}$ steady state inventory of sows at physiological state i in the $n' \in I$ sow farm
$p_{ij}^{n'}$: transition probabilities from i to j, with $i,j \in S$, in the $n \in I$ sow farm
$K^{n'}$: capacity in number of sows for farm n'
$I^{n'}[e][t]$: inventory of piglets of age $e \in E_I$ at week t in the $n' \in I$ sow farm per genotype
$A^{n'}[t]$: inventory of weaned piglets at week t in the $n' \in I$ sow farm to be transferred to the phase II
LS: average litter size at farrowing
p: pork Price in each period
s: slaughterhouse
$\pi_8^{n'}$: number of sows to take to the slaughterhouse
k^I : number or trucks to use to transport the sows from the farm to the slaughterhouse
kw^{III} : maximum weight a truck can transport from the farms to the slaughterhouse
qw^{III} : average weight of each sow when is lead to the slaughterhouse

Constraints are representing:

(1) All sows in period i able to go forward to the next period j do.
(2) Sum of all sows in all periods for the farm n' must not exceed the n' farm capacity
(3) All piglets in a lactation period e go forward next period $e+1$ per genotype
(4) The number of piglets to be transferred to phase II cannot exceed the number of piglets in the last lactation period.
(5) The number of piglet births are calculated as the number of sows multiplied by the coefficient LS
(6) Initial inventory per genotype
(7) Number of trucks used to bring sows
(8) Maximum weight of the trucks used to bring the sows

2.5.- Model for rearing farms: $c^{II}[t]$

Basically costs for rearing farms will be calculated according the inventory of animals for each farm n, stage e and period t. The cost corresponds to an amount per period of time, in this case week.
Moreover transport costs to transfer from sows farms (phase I) to rearing farms (phase II) are calculated according the number of animals at their last stage. Therefore:

$$\sum_{t=1}^{T} c^{II}[t] = \sum_{n''=1}^{N_{II}} \left(\overbrace{\sum_{e=1}^{E_{II}} \sum_{t=1}^{T} \sum_{g=1}^{G} c_e^{n''} I^{n''}[e][t][g]}^{piglets} + \overbrace{\sum_{t=1}^{T} k^{n''}[t][E] \cdot c_v^{n^{II}} \cdot d(n', n'')}^{transportation} \right)$$

$subject$ to:

$$I^{n''}[e+1][t][g] \leq I^{n''}[e][t-1][g] \qquad e \in \{1,\dots,E_{II}\}, t \in \{1,\dots,T\}, g \in \{1,\dots,G\}, n'' \in II \tag{9}$$

$$\sum_{e=1}^{E_{II}} \sum_{g=1}^{G} I^{n''}[e][t][g] \leq K^{n''} \qquad t \in \{1,\dots,T\}, n'' \in II \tag{10}$$

$$I^{n''}[1][t][g] = p[n''] \cdot \sum_{g'=1}^{G} A_t^{n''}[g'] \cdot g'[g] \qquad t \in \{1,...,T\}, g \in \{1,...,G\}, n'' \in II \tag{11}$$

$$I^{n''}[e][0][g] = I_e^{n''}[g] \qquad e \in \{1,...,E_{II}\}, g \in \{1,...,G\}, n'' \in II \tag{12}$$

$$A^{n''}[t][g] = \sum_{t=1}^{T} A_{n'}^{n''}[t][g] \qquad t \in \{1,...,T\}, g \in \{1,...,G\}, n'' \in II \tag{13}$$

$$\sum_{e=1}^{e^{II}} q^n[t][e][g] <= \sum_{e=1}^{e^{II}} I^{n^{II}}[E_{II}][t][g] \qquad t \in \{1,...,T\}, g \in \{1,...,G\}, n'' \in II \tag{14}$$

$$q^n[t][e] <= k^{II} * kk^{II} \qquad e \in \{1,...,E_{II}\}, t \in \{1,...,T\}, n'' \in II \tag{15}$$

$$q^n[t][e] * qw^{II} <= k^{II} * kw^{II} \qquad e \in \{1,...,E_{II}\}, t \in \{1,...,T\}, n'' \in II \tag{16}$$

Where:
II: set of rearing farms
T: time horizon in weeks
E_{II}: number of weeks for the rearing period
G: Genotypes
$I^{n''}[e][t]$: inventory of pigs of age e∈EII at week t in the n''∈II fattening farm
An'' [t]: inventory of new pigs entering at week t
Kn''[t]: capacity of the n''∈II fattening farm
$I_e^{n''}$: initial inventory of pigs at week t=0
$g'[g]$: grouping genotypes allowed. See table 1
$p[n'']$: transfer policy. See table 2.
$c_e^{n''}$: unitary cost per week related to pigs
$c_v^{n''}$: unitary cost per week related to pig transport. Cost per truck
k^I : number or trucks to use to transport animals from the rearing farms n to the fattering farms
kw^{II} : maximum weight a truck can transport from sow farms to rearing farms
qw^I : average weight of each sow when is lead from sow farms to rearing farms

Constraints are representing:

(9) All the pigs in a period *e* go forward next period *e+1*
(10) Animals in all stages *e* and periods *t* for the farm *n'* must not exceed the *n'* farm capacity
(11) Animals in farm *n* and stage *e* for a period *n* must be the total entering animals in farm *n*.
(12) Animals at the first period equals the piglets stock given
(13) Animals transported from the sow farms (phase *I)* in a period *t* must be the initial inventory
(14) Animals from a farm *n* in a period *t* must not be higher than the inventory at last stage for the farm *m* in the period *t*
(15) Number of trucks used to bring sows
(16) Maximum weight of the trucks used to bring the sows

2.6.- Model for fattering farms: $c^{III}[t]$

Fattering farms cost's estructure is basically like rearing farms. Feeding, medical costs will be calculated according the animal's aniventory for each farm *n*, stage *e* and period *t*. Transportation costs to transfer from rearing farms (phase *II*) to fattering farms (phase *III*) are calculated according the number of animals transfered. Therefore:

$$\sum_{t=1}^{T} c^{III}[t] = \sum_{n'''=1}^{N_{III}} \left(\overbrace{\sum_{e=1}^{E_{III}} \sum_{t=1}^{T} \sum_{g=1}^{G} c_e^{n'''} I^{n'''}[e][t][g]}^{piglets} + \overbrace{\sum_{t=1}^{T} k^{n'''}[t][E] \cdot c_v^{n'III} \cdot d(n'',n''')}^{transportation} \right)$$

subject to:

$$I^{n'''}[e+1][t][g] \le I^{n'''}[e][t-1][g] \qquad e \in \{1,\dots,E_{III}\}, t \in \{1,\dots,T\}, t \in \{1,\dots,G\}, n''' \in II. \qquad (17)$$

$$\sum_{e=1}^{E_{III}} \sum_{g=1}^{G} I^{n'''}[e][t][g] \le K^{n'''} \qquad t \in \{1,\dots,T\}, n''' \in III \qquad (18)$$

$$I^{n'''}[1][t][g] = p[n''] \cdot \sum_{g'=1}^{G} A_t^{n''}[g'] \cdot g'[g] \qquad t \in \{1,\dots,T\}, g \in \{1,\dots,G\}, n''' \in III \qquad (19)$$

$$I^{n'''}[e][0][g] = I_e^{n'''}[g] \qquad e \in \{1,\dots,E_{III}\}, g \in \{1,\dots,G\}, n'' \in III \qquad (20)$$

$$A^{n'''}[t][g] = \sum_{t=1}^{T} A_{n'i}^{n'''}[t][g] \qquad t \in \{1,\dots,T\}, g \in \{1,\dots,G\}, n'' \in II, n''' \in III \qquad (21)$$

$$\sum_{e=1}^{e^{III}} q^n[t][e] <= \sum_{e=1}^{e^{III}} I^{n^{III}}[E_{III}][t] \qquad t \in \{1,\dots,T\}, n''' \in III \qquad (22)$$

$$q^n[t][e] <= k^{III} * kk^{III} \qquad e \in \{1,\dots,E_{III}\}, t \in \{1,\dots,T\}, n''' \in III \qquad (23)$$

$$q^n[t][e] * qw^{III} <= k^{III} * kw^{III} \qquad e \in \{1,\dots,E_{III}\}, t \in \{1,\dots,T\}, n''' \in III \qquad (24)$$

where:
III: set of fattening farms
T: time horizon in weeks
G: Genotypes
E_{III}: number of weeks for the fattering period
$I^{n'''}[e][t]$: inventory of pigs of age e∈EIII at week t in the n'''∈III fattening farm
$A^{n'''}[t]$: inventory of new pigs entering at week t
$K^{n'''}[t]$: capacity of the n'''∈III fattening farm
$I_e^{n'''}$ initial inventory of pigs at week t=0
$g'[g]$: grouping genotypes allowed. See table 1
$p[n'']$: transfer policy. See table 2.
$c_e^{n'''}$: unitary cost per week related to pigs
$c_v^{n''}$: unitary cost per week related to pig transport. Cost per truck
k^{II} : number or trucks to use to transport animals from the rearing farms n to the fattering farms
kw^{III} : maximum weight a truck can transport from rearing farms to fattering farms
qw^{III} : average weight of each sow when is lead from rearing farms to fattering farms

Constraints are representing:

(17) All the pigs in a period *e* go forward next period *e+1*
(18) Sum of all animals in all stages *e* and periods *t* for the farm *n'* must not exceed the *n'* farm capacity
(19) The animal's inventory in farm *n* and stage *e* for a period *n* must be the total entering animals in farm *n*.
(20) Animals at the first period equals the piglets stock givent
(21) Animals transported from the sow farms (phase *I)* in a period *t* must be the initial inventory
(22) Animals to be transported from a farm *n* in a period *t* must not be higher than the inventory

at last stage for the farm *m* in the period *t*
(23) Number of trucks used to bring sows
(24) Maximum weight of the trucks used to bring the sows

2.7.- Income model: $v\ [t]$

The incoming model is based on the animal's sales price and demand for all the set of fattering farms. Both, price and demand will remain constant inside each period, but may vary between them. Transportation cost from the fattering farms to the slaughterhouse is taken into account at this moment and are substracted from the incomings.. Therefore:

$$\sum_{t=1}^{T} v\ [t] = \sum_{t=1}^{T}\left(\overbrace{\left(p[t]*\sum_{e=1}^{e^{III}} q[t][e]\right)}^{income} - \overbrace{\left(\sum_{e=1}^{e^{III}} k^{III}[t][e]*c_v^{n^{III}}*d(n''',s)\right)}^{transportation}\right)$$

$subject\ \text{to}:$

$$\sum_{e=1}^{e^{III}} q[t][\mathrm{e}] <= \sum_{e=1}^{e^{III}} I^{n^{III}}[\mathrm{E_{III}}][t] \qquad e\in\{1,...,E_{III}\}, t\in\{1,...,T\}, n'''\in III \qquad (25)$$

$$\sum_{e=1}^{e^{III}} q[t][e] <= \sum_{t^d=1}^{t} d[t^d] - \sum_{t^d=1}^{t-1} q[t^d] \qquad e\in\{1,...,E_{III}\}, t\in\{1,...,T\}, n'''\in III \qquad (26)$$

$$q[\mathrm{t}][\mathrm{e}] <= k^{III} * kk^{III} \qquad e\in\{1,...,E_{III}\}, t\in\{1,...,T\}, n'''\in III \qquad (27)$$

$$q[\mathrm{t}][\mathrm{e}]*qw^{VI} <= k^{III} * kw^{IV} \qquad e\in\{1,...,E_{III}\}, t\in\{1,...,T\}, n'''\in III \qquad (28)$$

where:
T: time horizon in weeks
p[t]: pork price at the period *t*
E_{III}: number of weeks for the fattering period
kk^{III} : capacity in number of animals a truck can transport from fattering farms to the slaughterhouse.
k^{III} : number of trucks to use to transfer the animals from a farm e to the slaughterhouse.
$\sum_{e=1}^{e^{III}} q[t][e]$: quantity of pork alowed to lead to the slaughterhouse
$\sum_{e=1}^{e^{III}} k^{III}[t][e]$: number of truck to use to transfer the animals for a n fattering farm to the slaughterhouse.
$I^{n^{III}}[E_{III}][t]$ number of animals at the last period for a fattering farm *n*.
t^d : periods from the beginning to the actual period
$\sum_{t^d=1}^{t} d[t^d]$ sum of the demand from the first period to actual one
$c_V^{n'''}$: unitary cost per week related to pig transport. Cost per truck
$\sum_{t^d=1}^{t-1} q[t^d]$ sum of the total quantity led to the slaughterhouse from the first period until actual.
$p[n'']$: transfer policy. See table 2.

s: slaughterhouse

kw^{IV} : maximum weight a truck can transport from rearing farms to fattering farms

qw^{IV} : average weight of each sow when is lead from rearing farms to fattering farms

Constraints are representing:

(25) The number of animals to transfer to the slaughterhouse must not be higher than the sum of all animals in last fattering period for all the farms
(26) The number of animals transfered to the slaughterhouse must be less or equal than the demand for period t plus previous demand not satisfied.
(27) Number of trucks used to bring sows
(28) Maximum weight of the trucks used to bring the sows

3.- Outlook

Next step is to refine the model using real data taken from a set of farms. This will allow to validate the output data from the model and compare it with previous, present and future data. Furthermore the extension of the present model into a stochastic linear programming model is in the agenda.

In this case the time horizon of interest is of one year. However, the time horizon considered is of three years to avoid the effect of boundary constrains at the end of the time horizon. Another consequence of that is the update of the model and the solving in a rolling time implementation. The model is implemented by using the modeling languaje ILOG OPL v.8.6.0. andsolved with the solver CPLEX v.12.2. Model data is managed with Microsoft Excel being used in both, input and output data storage due to the use-friendly interface.

Expected results are to be promising and of interest for the sector that is giving support.

4.- Acknowledgements

The authors acknowledge the financial support of the Spanish Research Program (AGL2010-20820 and MTM2009-14087-C04-01).

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