Simulation Model for *Salmonella* Typhimurium on a Farrow-to-Finish Herd

Correia-Gomes, C.[1,2*], Economou, T.[3], Bailey, T.[3], Brazdil, P.[4], Vieira-Pinto, M.[5], Niza-Ribeiro, J.[1,6]

[1]*ICBAS-UP, Universidade do Porto, Rua de Jorge Viterbo Ferreira,* nº228, 4050-313 Porto, Portugal
[2] *ERU-SRUC, Scotland's Rural College, Drummondhill, Inverness, IV2 4JZ, UK*
[3] *CEMPS, University of Exeter, Harrison Building, North Park Road, Exeter, EX4 4QF, UK*
[4] *LIAAD – INESC Porto L.A. Universidade do Porto, Rua de Ceuta, 118, 6º, 4050-190 Porto, Portugal*
[5] *UTAD, Veterinary Science Department, Apartado 1013, 5001-801 Vila Real, Portugal*
[6] *ISPUP – Institute of Public Health – Universidade do Porto, Rua das Taipas, 4099-003 Porto, Portugal*
**Corresponding author: carla.gomes@sruc.ac.uk*

Abstract
A stochastic model which simulates the dynamics of *Salmonella* Typhimurium in moderate to highly infected farrow-to-finish farms in Portugal was developed. The model comprises six different stages: three at the reproductive phase (sows) and another three for pig growth. Infection dynamics of *Salmonella* are modelled for each stage with four infection transition parameters: susceptible to infectious (β), infectious to carriers (α), carriers to infectious (δ), and carriers to susceptible (θ); and thee health status: susceptible, infectious and carrier. The infection transition parameters were estimated based on field conditions and the ones that influence the infectious state the most, at the end of the fattening stage, were: the transition rate from susceptible to infectious (β) in all pig-compartments, and the piglets' immunity protective factor. Several control measures can be suggested to reduce the effect from those parameters. The simulation model, if coupled with an economic model can then be used to test control measures, in terms of their cost-benefit, and the reduction of the prevalence in these moderated to highly infected farms will have an impact on human burden. The simulation model is flexible enough to introduce changes in the parameter values appropriately if future research and changes in the legislation so require. The model can also be adapted to different types of production (e.g. breeding, weaners or finishers units) as it was built in a compartmental way.

Introduction
Salmonella spp. is one of the major causes of food-borne outbreaks in the world (the second cause in Europe). As such, its control was considered necessary by the European food-safety policy makers under the EC Regulation 2160/2003. In practice, however, the control of this agent has proved to be difficult and expensive at farm level. Consequently the evaluation of the efficiency of control strategies for this agent has become an important and stringent issue, as stated in recent reports (Consortium, F. 2010). Modelling the dynamics of *Salmonella spp*. in pigs can be useful when assessing alternative control strategies. Susceptible – Infectious – Resistant (SIR) models are attractive tools in assessing the disease dynamics. The SIR model describes the dynamic of different states of individuals in the population in terms of a system of ordinary differential equations. The variables in the system are given by three compartments: susceptible group (S), infectious group (I) and carrier group (R). The aims of this study were: a) to develop a stochastic model which incorporates a production model with an infection model (the production model simulates the management procedures of an average farrow-to-finish Portuguese pig farm, while the infection model simulates the *Salmonella* Typhimurium infection in the farm); and b) to identify the parameters which influence most the model results at different compartments and stages of life within these compartments. The ones which influence most the infectious state at fattening stage were: the transition rate from susceptible to infectious (β) in all pig-compartments, and the piglets' immunity protective factor.

Material and Methods
The model simulates a farrowing-to-finish herd in which batch farrowing is applied to sows, leading to batch management of pigs. In these herds the complete life cycle of sows is considered, from the time they are recruited until they are culled; also the same for pigs, from their birth till slaughter. The duration of the sow reproduction cycle depends of the weaning time of the piglets which was fixed at 4 weeks. The pig growth period was fixed at 26 weeks. The modelling unit was the batch (for sows and pigs) and the time unit was one week. The reproduction cycle was divided in three stages (mating period, gestation period and farrowing/suckling period) corresponding to the occupation of three different types of rooms. Each batch of pigs composed of the litters from the batch of sows. The pig growth was divided in three stages (sucking period, post-weaning period and fattening period) corresponding to the occupation of three different types of rooms. All animals simultaneously leave the room they occupied except for the sows which abort at gestation. Mortality, culling, insem-

ination failure, abortion and litter size were the production variables modelled using a binomial distribution. The infection model was based on a SIR model for S*almonella*. Direct transmission between the pigs in the batch was assumed as well as indirect transmission via contaminated floor, rodents, etc. The transmission parameters considered were the transition from S to I (β), the transition from I to R (α), the transition from R to I (δ), and the transition from R to S (θ). Due to the short life span of pigs, it was assumed that they could not experience the transition from carrier to susceptible. The binomial distribution was used to simulate the transition S to I, and I to R. For the transition R to I; and R to S, Poisson distributions were used. For the transition S to I, a cohort time-dependent random effect was included to emulate the dynamic structure of the spreading of infection within cohorts, where the velocity of infection dependents on the number of susceptible and infectious animals in the previous time step. In the sensitivity analysis of the model, all the production variables and infection parameters were increased and decreased by 50% and the results were compared with the original results from the unperturbed parameters. The values and sources of the model variables and parameters are shown in Table 1.

Table 1: Model variables and parameters

Variables and parameters		Random/fixed	Value	Reference
Average number of sows per herd		Fixed	264	a, b
Median number of pig per pen	Post-weaning	Fixed	25	a
	Fattening	Fixed	17	a
Duration (weeks)	Mating	Fixed	6	c
	Gestation	Fixed	10	c
	Farrowing - sows	Fixed	5	c
	Maternity - piglets	Fixed	4	b
	Post-weaning	Fixed	8	c
	Fattening	Fixed	14	c
Mortality probability (per week)	Mating	Fixed	0.000833	c
	Gestation	Fixed	0.00357	c
	Farrowing – sows	Fixed	0.001786	c
	Farrowing – piglets	Fixed	0.0275	b
	Post-Weaning	Fixed	0.00375	a
	Fattening	Fixed	0.00357	a
Artificial insemination success probability – applied in the end of mating (pins)		Squared root of a Weibull distribution	10.31 (mean), 0.77 (sd)	b
Abortion probability (per week)		Fixed	0.0025	c
Culling probability	After failing insemination	Fixed	0.017 at end of mating	c
	After abortion	Fixed	0.017/week	c
	Voluntary culling	Fixed	0.333 at end of farrowing	c
Litter size		Normal distribution (the final value was rounded)	10.45 (mean), 0.87 (sd)	b
Transmission parameter or transition rate from susceptible to infectious (β)		Random (posterior distribution)	0.34/week [0.17-0.66]	d
Transmission parameter or transition rate from infectious to carrier (α)		Random (posterior distribution)	0.27/week [0.24 – 0.30]	d
Transmission parameter or transition rate from carrier to infectious (δ)		Random (posterior distribution)	0.09/week [0.008 – 0.21]	d
Transmission parameter or transition rate from carrier to susceptible (θ)		Fixed	0.06/week	Soumpasis and Butler, 2009
Cohort time-dependent random effect (σ^2_β)		Normal distribution	0 (mean), 1.29 (sd)	d
Piglets' protective factor due to sows passive immunity (pf)		Fixed (1/70 days)	0.1/week	Beloeil et al, 2003

Legend: sd – standard deviation, [a] Baptista et al, unpublished results of a survey to 109 herds in Portugal in 2009, [b] Production data of 200 Portuguese herds, collected by a software company from 2004 to 2006, [c] Expert opinion, [d] Correia-Gomes et al, unpublished.

Results

Results are shown in Table 2. The proportion of infectious sows was similar within the different rooms. There was an increase on the prevalence of infectious and carrier pigs along time for the pig compartment (piglets, growers and finishers), while the number of susceptible pigs went down. The prevalence of infectious animals in the pig compartment is lower than the prevalence of infectious sows in the sow

compartment (mating, gestation and farrowing). The parameter α and θ were the most influential for the sow compartment. For the pig compartments, parameter β and variable "passive immunity" were most influential for the pig part.

Table 2: Results for the infection state in each room for the sows and pigs

Production stage	Infection State	Results in proportions				Parameters with highest impact on the results
		Mean	SD	95% CI		
				LL	UL	
Mating	Susceptible	0.19	0.13	0.0	0.45	θ (mating/sows)
	Infectious	0.55	0.16	0.22	0.88	α (mating/sows)
	Carrier	0.26	0.14	0.0	0.56	α and θ (sows)
Gestation	Susceptible	0.23	0.16	0.0	0.60	α and θ (sows) + θ (gestation)
	Infectious	0.51	0.19	0.13	0.88	α (gestation/sows)
	Carrier	0.26	0.14	0.0	0.57	θ (gestation/sows)
Farrowing	Susceptible	0.16	0.16	0.0	0.50	β, α and θ (sows)
	Infectious	0.57	0.21	0.17	1.0	α (sows)
	Carrier	0.27	0.19	0.0	0.67	θ (sows)
Piglets	Susceptible	0.91	0.09	0.70	1.0	β (piglets)
	Infectious	0.09	0.09	0.0	0.30	β (piglets) + passive immunity
Growers	Susceptible	0.80	0.20	0.35	1.0	β (pigs)
	Infectious	0.19	0.19	0.0	0.64	β (pigs)
	Carrier	0.003	0.007	0.0	0.02	α (post-weaning)
Finishers	Susceptible	0.68	0.27	0.17	1.0	β (pigs)
	Infectious	0.31	0.26	0.0	0.8	β (pigs)
	Carrier	0.01	0.02	0.0	0.05	α (pigs)

Legend: SD – standard deviation, LL – lower limit, UL – upper limit, β – transition rate parameter from susceptible to infectious, α – transition rate parameter from infectious to carrier, δ – transition rate parameter from carrier to infectious, θ – transition rate parameter from carrier to susceptible

Discussion

The predicted prevalence for the infectious animals, in the sow-compartment is higher than the predicted prevalence of infectious animals in the pig-compartment. The same trend was observed in the Portuguese Baseline Studies (EFSA, 2008 and EFSA, 2009) for *Salmonella* Typhimurium. The prevalence of infectious animals at the end of the fattening period can be reduced using several control measures (such as increasing the cleaning frequently of the pen floor, reducing stock density per pen, minimizing the mixture of litters at post-weaning and fattening, and the control of rodents and other vectors) which influence the β parameter. The increase of the piglets' passive immunity can be achieved by allowing the correct consumption of colostrum by the piglets and decreasing the risk of concomitant diseases. The results of the sensitivity analysis have shown that the parameters which depended on expert opinion have not caused a major change in the results of the simulation model.

Conclusion

The simulation model potentially allows estimation of cost-benefit control measures if coupled to an economic model. The simulation model is flexible enough to introduce changes in the parameter distributions or values if future research and legislation so require. At the same time the model can be adapted to different types of production (e.g. breeding units, finisher units) as it was built in a compartmental way.

References

Beloeil P.A., Chauvin C., Proux K., Rose N., Queguiner S., Eveno E., Houdayer C., Rose V., Fravalo P., Madec F.. 2003. Longitudinal serological responses to Salmonella enterica of growing pigs in a subclinically infected herd, Prev Vet Med, 60, 207-226.

Consortium, F. 2010. Analysis of the costs and benefits of setting a target for the reduction of Salmonella in slaughter pigs for European Commission Health and Consumers Directorate-General SANCO/2008/E2/036 Final Report, 1-198.

EFSA, 2008. Report of the Task Force on Zoonoses Data Collection on the analysis of the baseline survey on the prevalence of Salmonella in slaughter pigs, PartA. The EFSA Journal 135, 111.

EFSA, 2009. Analysis of the baseline survey on the prevalence of Salmonella in holdings with breeding pigs, in the EU, 2008, Part A: Salmonella prevalence estimates. EFSA Journal 7, 1377.

Soumpasis I., Butler F. 2009. Development and Application of a Stochastic Epidemic Model for the Transmission of Salmonella Typhimurium at the Farm Level of the Pork Production Chain, Risk Anal., 29 (11), 1521-1533.