Journal of Agricultural and Applied Economics, 45,1(February 2013):125–138

Economies of Capacity Use in Decontamination of Pig Carcasses

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This article analyzes the economies of capacity use regarding hot water decontamination to reduce postslaughter risk of pathogens in meat, taking interfarm heterogeneities of *Salmonella* risk and costs of transportation into account, using Denmark as a case study. If risk reduction goals are stated at the processing plant level, then the exploitation of the favorable cost-effectiveness properties of hot water slaughtering requires fairly ambitious risk reduction goals and thus high use of decontamination capacity. If instead risk reduction goals are formulated for the sector as a whole, the cost-effectiveness properties can be exploited even for relatively low-risk reduction goals.

Key Words: capacity use, decontamination, costs, spatial economics

JEL Classifications: D24, Q13, R12

Salmonella is acknowledged as a major food safety problem in pork sectors in many countries. Several initiatives are taken to reduce these problems in primary production as well as at the processing stage (Goldbach and Alban, 2006), but it is still a policy aim to reduce the *Salmonella* risk further. The policy focus on *Salmonella* reduction is also present in Denmark. In particular, the most recent Danish *Salmonella* Action Plan of 2009 states that the postslaughter *Salmonella* prevalence in pork should be less than 1% (Danish Food Agency, 2009). Goldbach and Alban (2006), Nielsen et al. (2005) as well as the Danish pig industry have however ascertained that significant further reduction in the *Salmonella* prevalence in primary pig production will be difficult and costly to obtain and that such reduction is best accomplished at the processing plants (slaughterhouses) using decontamination technologies.

Decontamination is relevant if the prevalence of pathogens on carcasses is to be reduced to an extent that is not obtainable by improved slaughter hygiene and farm-level interventions. So far, the use of decontamination of fresh pork is not common in the European Union, but the European Commission has made decontamination possible through the Regulation of Hygiene in Animal Foods (Anonymous, 2004). The Danish Meat Association and the Danish Meat Research Institute have documented the microbiological effects of hot water slaughtering methods on *Escherichia coli* and *Salmonella* (Jensen and Christensen, 2000). At present, only carcasses from farms with the multiresistant *Salmonella typhimurium DT104* or from highly contaminated pig farms (so-called level 3 farms), representing approximately

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This article has been prepared as part of the research project *Efficacy, Cost Benefit, and Consumer Perception of Post Harvest Pathogen Reduction of Fresh Pork (DECONT)*, which was funded by the Danish Ministry of Food, Agriculture and Fisheries.

1% of the total pig production, are decontaminated using hot water slaughtering in Denmark (Nielsen et al., 2001).

Efficient improvement of the food safety also involves economic considerations. The economic issue is how to best reach the goal of a safer food supply at the lowest costs. Economic consequences of pathogen reduction technologies have been investigated in a number of studies. Goldbach and Alban (2006) compare hot water decontamination with sanitary slaughter and different feeding strategies in the Danish pork sector, finding that the benefit–cost ratio is substantially higher for hot water decontamination than for the other strategies. Jensen, Unnevehr, and Gomez (1998) conducted cost-effectiveness analysis for U.S. beef and pork processing sectors of 11 single pathogen reduction technologies or combinations of these using least cost curves, and Jensen and Unnevehr (2000) have demonstrated the application of a cost minimization model to identify the most cost-effective technologies in U.S. pork plants, evaluating the effects on aerobic bacteria and *Enterobactereaceae*. In a third U.S. study, Malcolm et al. (2004) evaluated the costs and effectiveness of seven combinations of pathogen-reducing technologies, including dehiding, steam pasteurization, and irradiation on the beef slaughter line. Vosough et al. (2006) explored the ranking of interventions against pathogenic *E. coli* in Dutch commercial beef plants based on an epidemiological simulation model and cost data from the literature and expert information. van der Gaag et al. (2004) investigated the costs of different intervention methods, including decontamination, against *Salmonella* along the supply chain based on cost data collected from the Animal Husbandry Research Institute, scientific literature and interviews, and effectiveness data obtained from an epidemiological simulation model for the pork supply chain. In a recent study, Lawson et al. (2009) investigated the cost-effectiveness of different decontamination methods based on expert data regarding costs and microbiological research results regarding effectiveness of the decontamination methods.

The results from the cost-effectiveness studies suggest that increased food safety generally induces higher marginal costs for meat processing plants, but the additional costs resulting from decontamination are modest and account typically for approximately 1–2% of total plant costs (Jensen and Unnevehr, 2000; Jensen, Unnevehr, and Gomez, 1998; Lawson et al., 2009). Implementation of new food safety interventions have shown economies of scale properties that favor large meat companies (Malcolm et al., 2004; Unnevehr and Jensen, 1999).

Most of the considered studies evaluate the costs of decontamination assuming full use of the decontamination facilities, for example that all pig carcasses—positive as well as negative—are decontaminated and that no excess capacity exists. However, in situations in which the prevalence of pathogens is relatively low, and where it may be possible a priori to identify deliveries with relatively high pathogen risk, e.g. by identification of crucial risk factors, a more partial-scale approach might appear more sensible from an economic viewpoint.

If less than full-scale implementation of decontamination is applicable, the optimization of capacity use becomes a relevant strategy to consider, because the establishment of decontamination facilities involves considerable capital investment. The issue of capacity use of investments in decontamination technology has received remarkably little attention in the economic literature on food safety, although it is recognized that decontamination is often investment-intensive (e.g. Aymerich, Picouet, and Monfort, 2008). Some explanations might be that an operational definition of capacity use is difficult to obtain and that empirical use data are scarce and subject to many potential measurement errors (Nelson, 1989).

Despite these methodological challenges, the objective of this article is to investigate the economies of decontamination capacity use, in which capacity is defined as the maximum number of pigs that may be decontaminated by the technology per year. This objective is pursued by means of an economic optimization model that takes into account the stochastic nature of *Salmonella* risk as well as the geographical localization of processing plants and pig production. The Danish pork sector is used as an illustrative case.

The article is structured as follows. Section two discusses some capacity considerations regarding decontamination capacity, and section three presents the methodology and data for the present analysis. Results from the analysis are presented in section four, and the final section draws some conclusions and discusses some perspectives from the analysis.

Capacity Considerations Regarding Decontamination

As indicated by some of the mentioned studies, most of the available decontamination technologies involve considerable investment, which implies economies of scale that favor large processing plants. Hence, a general decontamination requirement in the pig sector might impose a relatively high cost on butchers and smaller plants, because their use of decontamination capacity becomes low compared with larger plants.[1] Furthermore, if the general pathogen prevalence is low, a full-scale decontamination requirement would imply that a considerable share of the pig production were decontaminated even if they would not carry critical amounts of pathogens.

To the extent that pig herds exhibiting relatively high pathogen risk can be identified before delivery to the processing plants, there may be room for optimizing the use of decontamination capacity by establishing a market that directs high-risk deliveries to plants with decontamination capacity and directing low-risk deliveries to plants without such capacity and possibly to avoid excessive investments in decontamination facilities.

Furthermore, a less than full-scale decontamination requirement may allow the redirection of potentially high-risk pig deliveries from small-scale processing plants to larger plants, thus enabling better use of decontamination capacity and economies of scale and a lower additional cost imposed on small-scale plants compared with large-scale plants. Instead, these small plants can pay a premium to larger plants to decontaminate their high-risk pig deliveries.

If redirection of pig deliveries is to be considered as an integral part of a decontamination strategy, it is necessary to consider transportation costs, which are closely linked to the geographical location of pig production and slaughtering capacity. The localization of Danish pig slaughtering plants is illustrated in Figure 1.

To a large extent, this localization matches the localization of primary production (Table 1). The majority of pig processing plants are located in the western parts of the country and only two plants (Ringsted and Rønne) on the eastern islands. A relatively new large plant with a slaughtering capacity of 4.4 million pigs per year has recently been established in Horsens, and it has a central location that enables deliveries from a relatively large part of the country, including Funen and large parts of southeastern Jutland.

Although the slaughtering capacity is located fairly close to the primary production, there may still be a potential for sharing decontamination capacity between different processing plants to reduce capacity costs, in particular among the plants located in the western part of the country.

Furthermore, costs of coordinating the supply of high-risk pig deliveries and the decontamination capacity at the individual processing plants in an incentive-compatible manner should be considered. This coordination involves identification of high-risk deliveries, localization of spare decontamination capacity, and connecting these within relatively short time limits. Such costs may include the operation of farm-level *Salmonella* monitoring systems, monitoring of decontamination capacity use on processing plants, and operating a marketplace for the trade of high-risk and low-risk pig deliveries. It may, however, be claimed that some of these monitoring costs might also apply as general food safety measures and should not necessarily be fully attributed to the optimization of decontamination capacity use.

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[1] There exist other decontamination technologies that might be more economically feasible for smaller processing plants. These methods are however based on chemical decontamination (e.g. lactic acid or trisodiumphosphate [TSP]), which is not considered acceptable by consumers and the public in Denmark and the European Union.

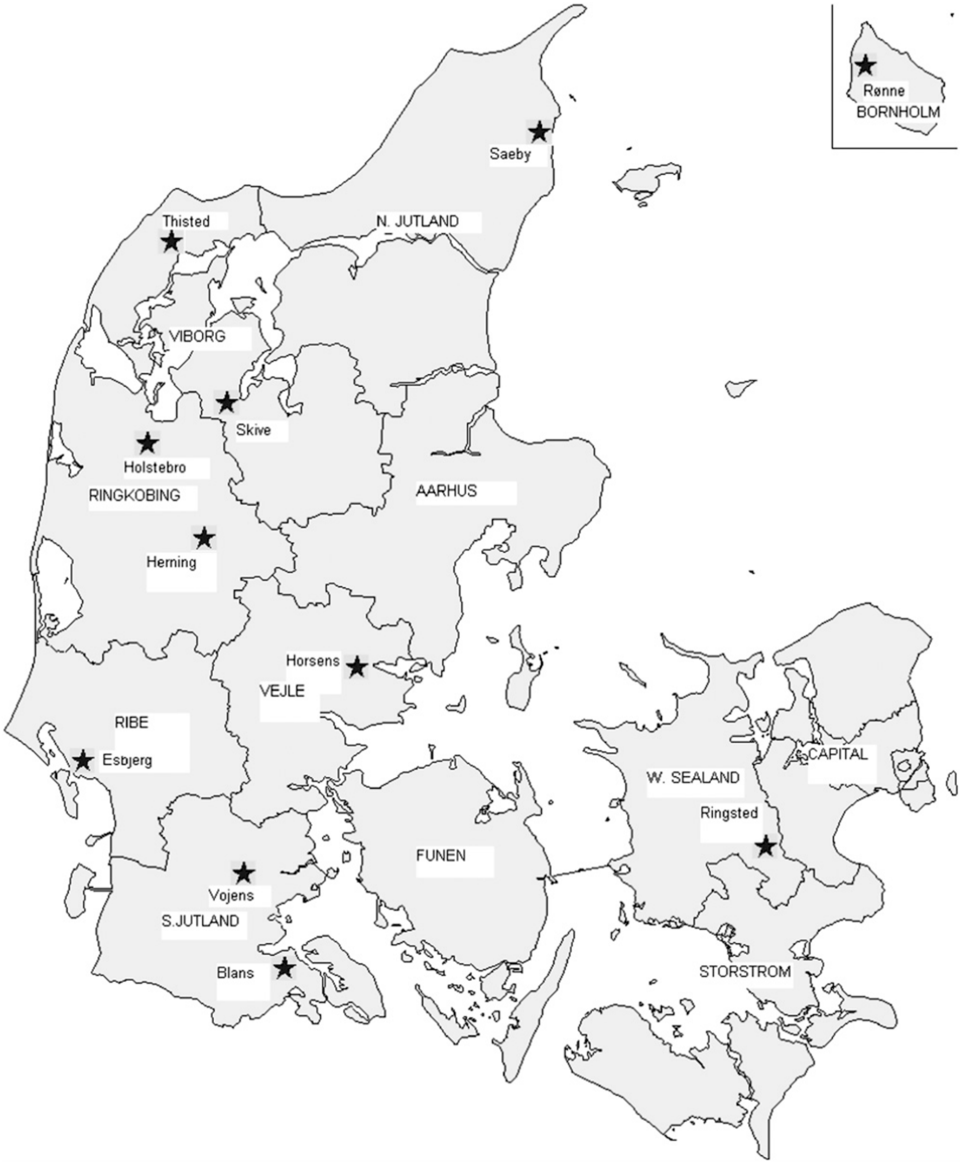

Figure 1. Localization of Larger Danish Processing Plants, 2006

The specific modeling of such coordination costs is beyond the scope of this article, but it should be recognized that if these costs are large, they may undermine the economic incentives to concentrate decontamination capacity on fewer plants. In the following, we assume that such coordination constitutes a fixed cost (independent of the number of pigs to be redirected) that does not exceed the potential cost-saving of better capacity use (net of transport costs).

Optimizing the use of decontamination capacity in the Danish *Salmonella* control strategy raises a number of research questions, including: 1) the extent of excess decontamination capacity for different *Salmonella* risk reduction targets; 2) the costs of underused decontamination capacity for different risk reduction targets; and 3) economic consequences of *Salmonella* risk reduction requirements at the plant level or the sector level, respectively.

Table 1. Primary Pig Production and Slaughtering Capacity, 2006

County	Produced Pigs (1,000s)	Processing Plant	Slaughtering Capacity (1,000s)
Capital region[a]	281	Blans	2,236
West Sealand	1,043	Esbjerg	1,544
Storstrøm	1,138	Holstebro	1,560
Bornholm	409	Herning	1,596
Funen	2,111	Horsens	4,420
South Jutland	2,527	Ringsted	3,026
Ribe	930	Rønne	442
Vejle	1,786	Skive	1,534
Ringkøbing	2,613	Sæby	2,340
Aarhus	2,302	Thisted	1,695
Viborg	2,511	Vojens	827
North Jutland	3,299		

[a] Capital region comprises the counties of Copenhagen, Frederiksborg, and Roskilde as well as the municipalities of Copenhagen and Frederiksberg.

Source: Statistics Denmark and the two major Danish pig slaughter companies, Danish Crown (www.danishcrown.dk) and Tican (www.tican.dk).

In the following, these research questions are pursued, taking into account the costs and *Salmonella* prevalence-reducing effects of hot water slaughtering as well as transportation costs, which take the geographical location of pig production and processing plants into consideration.

Methodology and Data

We investigate the stated research questions by means of an integrated microbiological–economic model framework, in which we combine the risk-reducing effects of decontamination with the costs of decontamination and transportation between pig producers and processing plants in a setting where the aim is to determine the cost-minimizing combination of decontamination capacity and transport patterns for given reductions in the risk of buying pork contaminated with *Salmonella*. The first subsection outlines this modeling framework, whereas the last subsection describes the calibration of the model in terms of data and parameters.

It should be noted that for the model's focus on the aggregate costs of decontamination and transportation to be realistic, we need some requirements on the incentive mechanisms working in the slaughtering sector, ensuring that the objective of overall cost minimization is incentive-compatible with the objectives that are pursued at the plant level. For the analysis, we assume that such incentives mechanisms are in place in terms of a price premium (or price discounts) paid by processing plants without decontamination capacity to plants receiving and decontaminating their high-risk pig deliveries and furthermore that costs of coordinating demand for and supply of decontamination capacity across plants do not exceed the potential cost savings from such coordination. We return to these issues in the final discussion.

Modeling Framework. We developed a mathematical programming model, in which hot water slaughtering is the only available type of intervention to reduce the prevalence of *Salmonella*. Hot water decontamination is done on the pig carcass right after slaughtering and before any further processing. Further processing of the carcass is assumed to take place in the chain after the pig slaughter. Furthermore, we assume that decontamination facilities will only be established on larger plants (i.e. plants processing more than 400,000 pigs per year), because the costs of establishing such facilities would be prohibitive for smaller plants. The sum of decontamination and transportation costs is minimized subject to a number of physical/technical constraints, including the geographical localization of primary pig production, the slaughtering capacity of the respective plants, technical–biological relationships between decontamination and *Salmonella* prevalence, and a policy constraint specifying an acceptable *Salmonella* prevalence level. Solving this problem yields the cost-minimizing size and geographical location of decontamination capacity to obtain the specified reduction in pathogen risk.

The costs of decontamination facilities at processing plants include fixed costs in terms of investment and installation costs during the construction of such facilities as well as variable costs in terms of operating costs such as energy, water, labor, cleaning, maintenance, etc., the latter depending on the number of carcasses. Hence, the total annual decontamination cost, C_d, is modeled as

$$(1) \qquad C_d = c_f \cdot D + c_v \cdot Y_d$$

The term c_f is the fixed annual cost per line of decontamination capacity, D is the number of slaughter lines with decontamination capacity, c_v is the variable decontamination cost per carcass, and Y_d is the total number of carcasses decontaminated.

It could be expected that capacity considerations would lead the slaughtering sector to concentrate the establishment of decontamination facilities on as few slaughter lines as possible. This might imply that not all pig processing plants would establish such facilities, but instead that some of the pig deliveries from "high-risk" producers would be redirected or sold (at a price premium or price discount) to plants possessing such capacity. The economic potential for such sharing of decontamination facilities, however, depends on the additional coordination and transportation costs (including associated additional costs, e.g. veterinary inspections, administration) that would be invoked by redirection of pig deliveries, which again depends on the distances from primary producers to the respective processing plants and on the ownership and organization of the plants.

For each combination of county b and processing plant a, we estimate the average transport distance, assuming that this distance comprises both a fixed and a variable part. Formally, the average transport distance m_{ba} from county b to plant a through border point e is represented as

$$(2) \qquad m_{ba} = m_{be} \cdot Y_{ba}/Y_b + m_{ea}$$

The fixed part of the distance (m_{ea}) represents the road distance from the border (e) of county b (where the most relevant road crosses the border) to plant a. The variable part of the distance ($m_{be} \cdot Y_{ba}/Y_b$) represents the average distance to the county border for the county's farmers delivering pigs to processing plant a. It is assumed that the variable part of the average distance depends positively on the share of pigs from county b delivered to plant a, Y_{ba}/Y_b, reflecting an underlying assumption that primarily those farms in county b with the shortest distance will tend to deliver to plant a. If the entire production of pigs from county b is delivered to plant a, the variable part of the average transport distance is estimated as the road distance between the geographical centre and the border of the county given by the term m_{be}. For a processing plant located within the county, the variable part of the average transport distance is estimated as the distance between the plant and the main border entrance to the county.

Assuming a unit cost, c_T, per pig per transported km, the total transportation cost, C_T, is thus represented by

$$(3) \qquad C_T = \sum\nolimits_b \sum\nolimits_a c_T \cdot Y_{ba} \cdot m_{ba}, \quad a \in \{\text{processing plants}\}, b \in \{\text{counties}\}$$

The prevalence of *Salmonella* in pigs (β) delivered from county b is assumed to be well described by a truncated normal distribution[2]:

$$(4) \qquad \beta_b \sim N^T\left(\bar{\beta}_b, \sigma_b^2\right)$$

and because it is further assumed that the *Salmonella* prevalence distribution in pigs delivered from county b to processing plant a is identical to the distribution for the county as a whole, the distribution of *Salmonella* prevalence at plant a is also normally distributed

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[2] The normal distribution assumption should be considered as a local approximation, because the prevalence is restricted to the range between 0 and 1 (De Vos, Saatkamp, and Ehlers, 2007, section 2.2.1).

$$\text{(5)} \quad \beta_a \sim N\left(\bar{\beta}_a, \sigma_a^2\right)$$

$$\bar{\beta}_a = \sum\nolimits_b Y_{ab} \cdot \bar{\beta}_b \Big/ \sum\nolimits_b Y_{ab}$$

$$\sigma_a^2 = \left(\sum\nolimits_b Y_{ab} \Big/ \sum\nolimits_v Y_{av}\right)^2 \cdot \sigma_b^2$$

Decontamination through hot water slaughtering reduces the prevalence of *Salmonella* positive carcasses by the fraction δ. That is, if the entire production of processing plant a is decontaminated, the mean prevalence after decontamination will be $(1-\delta)\cdot\bar{\beta}_a$.

Assume now a situation in which the fraction α of the pig production on processing plant a exhibits a *Salmonella* prevalence beyond a specified threshold β^*, where the expected prevalence in this fraction is termed $\bar{\beta}_U(\alpha)$, and where the expected prevalence of the fraction exhibiting below-threshold prevalence is given by $\bar{\beta}_L(\alpha)$. Note that these expected values depend on the fraction considered. Assume further that information making it possible a priori to identify those deliveries with above-threshold prevalence is available, e.g. by means of on-farm tests in pig herds or on the basis of identified risk factors. Such information will more likely be available at the herd level (rather than for the individual animal), so decisions to decontaminate or not will be at the batch level. To comply with a regulation stating the threshold level β^* to be the acceptable level, the processing plant may then have the choice of either establishing decontamination capacity to decontaminate the fraction of the production with above-threshold expected prevalence or to exchange pigs from above-threshold herds with pigs from below-threshold herds from another plant, which possesses spare decontamination capacity. If plant a chooses to decontaminate the fraction α_a^d, the resulting expected prevalence will be

$$\text{(6)} \quad \beta_a' = \alpha_a^d \cdot \bar{\beta}_U\left(\alpha_a^d\right)\cdot(1-\delta) + \left(1-\alpha_a^d\right)\cdot\bar{\beta}_L\left(\alpha_a^d\right)$$

Hence, the expected prevalence after decontamination is the weighted average of the expected prevalence in postdecontamination high-prevalence carcasses and the expected prevalence in untreated low-prevalence carcasses with the respective fractions as weights.

If instead processing plant a chooses to swap (possibly against a payment) its high-prevalence deliveries (the fraction α_a^f) with low-prevalence deliveries from another plant v (with spare decontamination facilities), the expected prevalence on the two plants will be

$$\begin{aligned} &\text{Processing plant a:} \beta_a' = \left(1-\alpha_a^f\right)\cdot\bar{\beta}_L\left(\alpha_a^f\right) \\ &\qquad + \alpha_a^f \cdot \bar{\beta}_L\left(\alpha_v^d\right) \\ &\text{Processing plant v:} \beta_v' = \Big(\tilde{\alpha}_a^f \cdot \bar{\beta}_U\left(\alpha_a^f\right) \\ \text{(7)} \qquad &\qquad + \alpha_v \cdot \bar{\beta}_U\left(\alpha_v^d\right)\Big)\cdot(1-\delta) \\ &\qquad + \left(1 - \tilde{\alpha}_a^f - \alpha_v^d\right) \\ &\qquad \cdot \bar{\beta}_L\left(\alpha_v^d\right) \\ &\tilde{\alpha}_a^f = a_a^f \cdot Y_a / Y_v \end{aligned}$$

Hence, an opportunity to redirect or trade high- or low-risk pig deliveries between processing plants divides the market for pig deliveries into two submarkets: a high-price market for low-risk deliveries that do not need to be decontaminated and a low-price market for high-risk deliveries, where carcasses will be decontaminated after slaughtering. Whether a plant chooses a strategy to slaughter and decontaminate pigs from high-risk herds in its own plant (like plant v shown previously) or a strategy to pay another plant to receive and decontaminate these high-risk pigs (like plant a shown previously) depends on the balance between the costs of in-house decontamination and the costs of redirecting the deliveries. Transportation costs are assumed to play a major role, but payment of decontamination fees may also have a role to play. If we assume that decontamination fees are determined to cover the marginal costs of decontamination (i.e. the c_V term shown previously), then the processing plant will choose to redirect its high-risk pig deliveries if the sum of decontamination fee and additional transportation costs are lower than the average cost per decontaminated pig of running its own facilities. On the other hand, if the marginal cost of further transportation is high, it will be most efficient to establish and run decontamination facilities in-house.

As mentioned previously, costs of coordinating demand and supply of high-risk and low-risk pig deliveries across processing plants may also influence the incentives to operate such a redirection scheme. Because we assume such costs to be fixed, they do not affect the incentives on the marginal pig delivery, but may of course play a role for the economic incentive to establish such a redirection scheme in the first place.

Assuming that it is possible a priori to identify the pig farms with relatively high *Salmonella* risk, and hence deliveries, the model determines the combination of delivery structure (between counties and processing plants) and the degree of implementing decontamination facilities in the plants that minimizes the total costs of transportation and decontamination while still satisfying constraints regarding production capacity, decontamination capacity, and specified *Salmonella* reduction requirements.

In the literature, quantitative analyses related to *Salmonella* and taking into account the stochastic nature of *Salmonella* prevalence are often based on stochastic simulation, in which distributions for prevalence resulting from various interventions are estimated by means of random draws from underlying epidemiology-derived distributions regarding base levels and intervention effects, respectively (see e.g. Bergevoet et al., 2009; van der Gaag et al., 2004). Provided correct assumptions of the underlying distributions, such models may often provide a reasonable representation of the resulting prevalence distribution. However, because the optimization framework in the present study includes the α -fractiles as decision variables, there is a need for a different approach because the model builds on various analytical derivatives of the distribution function, and the normal distribution is not very suitable for such calculus. Whereas Taylor-polynomial approximations may provide analytically tractable solutions to such problems locally, a good global approximation to the normal distribution is a transformed ("normalized") logistic distribution function $P(\beta' \le \beta) = e^{k\cdot\frac{\beta-\bar{\beta}}{\sigma_\beta}} \Big/ \left(1 + e^{k\cdot\frac{\beta-\bar{\beta}}{\sigma_\beta}}\right)$, where the parameter k (which adjusts the "fatness" of the distribution's tails) takes a value of 1.702 (Bowling et al., 2009).

The analytical model assumes that it is possible to redirect pig deliveries with certain risk characteristics to other processing plants on assessment of risk in the pig herds. In the case of the Danish pig sector, this is a reasonable approximation, because 10 of 11 processing plants, representing more than 90% of total slaughterings, are owned by one company, Danish Crown. The assumption might however also be reasonable in a setting where all processing plants were competitors. This would require a market and a price setting mechanism for the decontamination service, and this would pose requirements to the reliability of *Salmonella* risk information regarding pig herds delivering to the processing plants, but possibly also larger coordination costs. Hence, the economic incentives to operate such redirection schemes will differ between markets. In the present analysis, we assume that decontamination services are priced from a marginal cost principle. However, if only few slaughtering companies are large enough to use decontamination capacity properly, a problem of market power may emerge, which may complicate the coordination of decontamination capacity supply and demand and hence distort the incentives to use total decontamination capacity to a socially cost-effective extent.

Data. The theoretical model outlined in the previous section is calibrated on cost data for hot water slaughtering, data on pig transport distances between regions of primary production and location of processing plants in Denmark, and data on the *Salmonella* prevalence base level and effect of hot water slaughtering.

Cost data for hot water slaughtering are displayed in Table 2. Based on data from the Danish Meat Research Institute, it is assumed that the investment (including installation costs) amounts to 342,000 €[3] for establishing hot water decontamination on a slaughter line with a slaughtering capacity of 740,000 pigs per year. Assuming an interest rate at 3% and a 7 years' duration of the decontamination equipment, this implies an annual capital cost of 55,000 €, which is assumed to be independent of

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[3] 1 € = 1.3 U.S. $ in 2006.

Table 2. Cost Data for Hot Water Slaughtering

Capacity—1,000 carcasses/year	740
Investment (1000 EUR)	342
	1000 €/year
Capital cost	55
Variable costs (at full capacity use):	85
Energy and water cost	
Labor cost	25
Other variable costs	25
Total cost	190
	€/carcass
Variable costs per carcass	0.18
Total costs per carcass	0.26

Source: Danish Meat Research Institute.

the extent to which this decontamination capacity is used.

Variable costs of decontamination comprise energy, water, and labor as well as other costs such as cleaning, solution, etc. This amounts to 0.18 €/carcass. It is assumed that this cost per carcass is independent of capacity use and hence that the total variable costs are proportional to the number of carcasses decontaminated.

If the decontamination capacity is fully used, the total (fixed + variable) decontamination cost per carcass amounts to 0.26 €. On the other hand, if the capacity is less than fully use, the cost per carcass will be higher as a result of fixed costs' substantial proportion of total costs.

To quantify the transport costs, a matrix of distances between primary producers and processing plants (Table 3) has been estimated using the Danish counties[4] as the geographical basis for describing the location of primary producers. The distances are estimated using the open-source Internet roadmap service provided by Krak (2008).

Costs of transportation were estimated using standard figures provided by the Danish Ministry of Transports and Energy (2006). According to these figures, the total costs of lorry transport is 0.305 € per kilometer. Assuming that a lorry carries 100 pigs at the time, the transport unit cost (c_T) amounts to 0.003 €/km/pig. Hence, for example, the cost of transporting a pig from the Capital region to the Blans plant would amount to 297 × 0.003 = 0.95 €.

Salmonella seroprevalence in pigs was 9% in 2006 in Denmark. For carcasses leaving the slaughterline, the average *Salmonella* prevalence in 2006 was 2.24% according to the Danish National Food Institute. The standard deviation of the prevalence was assumed to be 0.2%. We assume that this distribution of *Salmonella* prevalence is identical across regions, and furthermore, we assume that it is possible to identify potentially high-risk pig herds with a precision of 50% using e.g. serological tests. Hot water decontamination after slaughtering reduces *Salmonella* prevalence by 90%. Hence, if full-scale decontamination were implemented, this would reduce the expected prevalence to 0.224%.

Results

For the analysis, we specify a range of accepted *Salmonella* risk levels ranging from the current level of 2.2% to a low of 0.2%, which represents the maximum obtainable reduction by means of hot water decontamination. It is assumed that each processing plant must comply with the respective accepted risk levels in the sense that its annual average should at maximum correspond with the specified risk level.

Results of these calculations are presented in Table 4. For a reduction from the current 2.2% to 2.04 by means of hot water decontamination, 1.3 million pig carcasses (approximately 6% of the entire production) must be decontaminated. As the *Salmonella* risk target is specified at the processing plant level, all plants must undertake actions to reduce *Salmonella* risk. This implies that even for this low level of risk reduction, decontamination capacity will be established on 11 slaughter lines, and a moderate number of pigs (4,000 heads) are redirected. The total annual cost of risk reduction amounts to 0.83 million €. If the decontamination capacity is only use to the extent that the specified risk

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[4] Since the beginning of 2007, the county structure was reformed, and the former 14 counties were replaced by five larger administrative regions. However, because the data for the present purpose refer to 2006, and because the former county structure provides a more detailed geographical description, we have chosen to use this structure as the basis for estimating transport distances.

Table 3. Average Transport Distances between Regions and Processing Plants (km)

Region/Plant	Blans	Esbjerg	Holstebro	Herning	Horsens	Ringsted	Rønne	Skive	Sæby	Thisted	Vojens
Capital region	297	284	334	298	353	49	210	333	455	404	255
West Sealand	269	255	305	270	224	48	248	305	426	375	227
Storstrøm	306	293	343	306	262	140	366	342	463	413	264
Bornholm	486	473	523	487	442	241	88	522	643	593	444
Funen	161	148	198	162	117	104	330	197	318	268	119
South Jutland	55	108	187	151	123	232	457	201	325	257	21
Ribe	103	26	164	99	115	224	450	178	316	234	60
Vejle	116	57	109	74	33	177	403	145	238	240	74
Ringkøbing	184	99	27	17	94	266	492	55	202	105	142
Aarhus	199	186	105	86	72	264	489	87	150	143	157
Viborg	254	145	52	55	127	319	544	50	172	59	193
North Jutland	289	276	147	141	162	354	579	106	52	93	247

Note: Transportation between Sealand and Funen/Jutland is assumed to pass Storebaelt. Transportation between Bornholm and other regions has been supplemented with 75 km as a representation of ferry transportation time.
Source: www.krak.dk.

reduction goal is met, the degree of capacity use is quite low, ranging from 5–57% between processing plants, which also means that the costs per decontaminated carcass are quite high for such a low reduction goal. Considering that only 6% of the carcasses are decontaminated, the maximum capacity use of 57% may appear high. However, such a high use is only realized on the Horsens plant, which processes almost 4.5 million pigs per year and operates a relatively large number of slaughter lines. For most of the other plants, the degree of use is in the range of 5–15%.

For more ambitious risk reduction goals, the cost of decontamination naturally increases, but so does the degree of capacity use. One exception from this general pattern is however seen when the risk level is reduced to 2%. In this case, the maximum capacity use (found in Horsens) is lower than for the 2.04% risk level, because a larger share of the contaminated pigs are redirected from Horsens to the adjacent plants.

If the risk level is reduced to 1%, the decontamination capacity on processing plants is used by between 47% and 94%, because the decontamination capacity necessary for this reduction goal is 16 slaughter lines (in contrast to 11 slaughter lines for the modest reduction goal stated previously), leading to an aggregate cost of 2.79 million € per year.

Decontamination of the entire pork production leads to a total annual cost of 5.39 million € and full use of decontamination capacity on all processing plants, and hence no redirection of pig deliveries between plants.

Table 4. Use of Decontamination Capacity and Costs and Processing Plant-Level Risk Reduction Requirement

Risk Level	2.04%	2.00%	1.50%	1.00%	0.50%	30.20%
Carcasses decontaminated (1,000 heads)	1,302	1,470	5,789	9,975	14,625	20,950
Pig deliveries redirected (1,000 heads)	4	33	315	533	686	—
Decontamination capacity (lines)	11	11	13	16	26	26
Minimum capacity use (percent)	5.2	6.9	27.3	47.2	68.6	100
Maximum capacity use (percent)	57.4	41.6	82.0	94.3	92.2	100
Decontamination cost (million EUR/year)	0.83	0.87	1.77	2.71	4.11	5.39
Extra transportation cost (million EUR/year)	0.00	0.01	0.05	0.08	0.10	0
Total cost (million EUR/year)	0.83	0.88	1.82	2.79	4.21	5.39

Sensitivity analyses with respect to the transport cost assumption show that the results are fairly robust to the assumption of 0.003 € per pig per kilometer transported. Robustness of the results with respect to decontamination technology—and hence the distribution of fixed and variable costs—has also been tested by replacing hot water slaughtering with lactic acid spraying (involving a fixed cost 10.000 €/year and a variable cost of 0.21 €/carcass), showing similar results.

In the results presented in Table 4, it is assumed that each processing plant must comply with the *Salmonella* risk reduction requirement, implying that each individual plant must be able to report annual average risk figures below the stated levels. As an alternative—and as a benchmark—consider now a regulation, in which the risk reduction requirement is imposed on the pork sector as a whole, i.e. the average postslaughter *Salmonella* risk reported for the sector as a whole should not exceed the specified level, but variation across plants is allowed. In such a case, plants are allowed to coordinate their establishing of decontamination capacity and hence to reduce the extent of underused decontamination capacity. Such a scenario might be claimed to be somewhat unrealistic at first glance, and it would involve a range of challenges related to information, incentives, and transaction costs, but it is not incompatible with e.g. the Danish goal for *Salmonella* control, as mentioned in the "Introduction."

Table 5 shows some key figures from such a sector-level requirement and compares them with corresponding figures for the previously described plant-level requirement. For small reductions in *Salmonella* risk, the total costs of decontamination are substantially lower—and the capacity use considerably higher—in case of a sector-level requirement. For larger risk reductions, the costs as well as the degree of capacity use for the two types of requirement tend to converge toward each other. In contrast, the unit costs induced by a sector level risk requirement are fairly independent of the magnitude of the risk reduction requirement.

Discussion

Postharvest carcass decontamination can be considered as a strategy to reduce pathogen risk in pork. If the prevalence of pathogens is high, it may make sense to require the establishment of full-scale decontamination capacity for the entire production. However, if the current pathogen level is modest, and if it is possible to differentiate pig herds according to risk level before delivery, it may be considered more reasonable to establish a less than full-scale decontamination capacity from an economic perspective.

In this article, we have developed an economic model for investigating the economies of capacity use regarding hot water slaughtering of pig carcasses. The model has been used for analyzing costs and capacity use for various *Salmonella* prevalence reduction requirements in Danish pig carcasses. As expected, the total costs increase with the magnitude of the reduction requirement.

Table 5. Costs and Use of Decontamination Capacity, Processing Plant-Level vs. Sector-Level Risk Reduction Requirement

Risk Level	2.04%	2.00%	1.50%	1.00%	0.50%	0.20%
Plant-level requirement						
Total cost (million EUR/year)	0.83	0.88	1.82	2.79	4.21	5.39
Unit cost (EUR/carcass)	0.61	0.57	0.31	0.28	0.29	0.26
Aggregate capacity use (percent)	15.7	17.7	58.7	82.3	74.2	100.0
Sector-level requirement						
Total cost (million EUR/year)	0.27	0.30	1.47	2.61	4.12	5.39
Unit cost (EUR/carcass)	0.21	0.20	0.25	0.26	0.28	0.26
Aggregate capacity use (percent)	81.9	95.5	76.4	84.9	76.9	100.0

However, the cost per decontaminated carcass is decreasing substantially with reduction requirements up to 25–30% if the reduction goal is stated for each individual processing plant, because each plant has to establish decontamination capacity of its own, even for modest risk reduction goals. Hence, although studies like Goldbach and Alban (2006) suggest that hot water slaughtering may be considered a dominating strategy from a cost-effectiveness perspective, compared with other strategies such as changed feeding, this may not necessarily be the case for moderate risk reduction goals. If, on the other hand, the risk reduction goal is stated for the sector as a whole, the sector's ability to optimize capacity use across plants improves significantly. For reduction goals exceeding approximately 30%, the economies of capacity use become less important; the cost per decontaminated carcass is approximately 0.30 €, showing only a slight decrease with the risk reduction aim.

As mentioned previously, establishing hot water slaughtering facilities requires fairly large investments, which is a relative disadvantage to small processing plants. With a less than full-scale implementation of decontamination as a tool to reduce *Salmonella* prevalence, and assuming that identification of high-risk pig deliveries is possible before delivery, it may be possible for these smaller plants to establish contracts with larger plants to swap high-risk deliveries with low-risk deliveries and hence avoid the costs of investing in their own decontamination facilities.

In the article's analyses, it is assumed that it is possible to identify high-risk pig herds before delivery at the slaughterhouse. Such identification can possibly be done on the basis of the herds' *Salmonella* history or by more formal risk factor analyses (e.g. Bollaerts et al., 2008; Poljak et al., 2008; Veerle et al., 2008). By means of such methods, it may be possible to classify pig herds in different risk classes with reasonable certainty. One way to ensure the objectivity and general recognition of such information would be to undertake testing and herd risk assessment as a collaborative action.

The analyses of this article rest on assumptions regarding the processing plants' economic incentives to reduce *Salmonella* prevalence through decontamination and to cooperate or trade with each other to minimize the costs induced by specified *Salmonella* reduction requirements. Further research to investigate the extent to which such incentives are in place, and how they could be established or enhanced, for example through the formation of contracts or establishing infrastructures that can facilitate coordination and reduce transaction costs, is recommended.

It has not been possible to estimate the coordination costs in this study, but the potential cost savings from improved capacity use constitute an upper limit if such coordination should be driven by economic incentives. Differences in the organization and spatial concentration of the pork sectors between countries or markets may imply that the economic incentives for redirecting high-risk pig deliveries between processing plants are favorable in some countries and less favorable in other countries. As mentioned, 10 of the 11 largest Danish pig plants are owned by one company, which may be expected to facilitate the coordination across plants and hence strengthen the economic incentive for such coordination compared with many other countries.

Incentive compatibility could be obtained or strengthened by a policy regulation shifting the balance between economic outcomes from compliance vs. noncompliance with specific thresholds, e.g. in terms of rewards on compliance or fines or compensation liability requirements in case of noncompliance. However, economic incentives may also be improved by contract designs (Martin, 1997) or interventions that reduce transaction costs associated with strategies that are cost-effective from a social point of view. One example of such intervention includes reduction of information asymmetries on herd-level *Salmonella* risk by establishing an officially authorized identification of high-risk pig herds. Another example is to reduce trade costs by facilitation of interplant trade with high-risk pig deliveries, e.g. by establishing an official marketplace for such trade. Other interventions might include an insurance scheme that would make the individual plants indifferent between in-house decontamination vs. redirection of high-risk pig deliveries at the margin or ex ante contracts between plants.

[Received December 2011; Accepted June 2012.]

References

Anonymous. “Regulation (EC) No. 853/2004 of the European Parliament and of the Council of April 29, 2004 Laying down Specific Hygiene Rules for Food of Animal Origin.” 2004.

Aymerich, T., P.A. Picouet, and J.M. Monfort. “Decontamination Technologies for Meat Products.” *Meat Science* 78(2008):114–29.

Bergevoet, R.H.M., G.v. Schaik, J. Velling, G.B.C. Backus, and P. Franken. “Economic and Epidemiological Evaluation of *Salmonella* Control in Dutch Dairy Herds.” *Preventive Veterinary Medicine* 89(2009):1–7.

Bollaerts, K., M. Aerts, S. Ribbens, Y. van der Stede, I. Boone, and K. Mintiens. “Identification of *Salmonella* High Risk Pig-herds in Belgium by Using Semiparametric Quantile Regression.” *Journal of the Royal Statistical Society. Series A, (Statistics in Society)* 171,2(2008): 449–64.

Bowling, S.R., M.T. Khasawneh, S. Kaewkuekool, and B.R. Cho. “A Logistic Approximation to the Cumulative Normal Distribution.” *Journal of Industrial Engineering and Management* 2,1(2009):114–27.

Danish Food Agency. “Salmonella Action Plan for Pigs 2009–2013.” (Fødevarestyrelsen, Salmonellahandlingsplan—svin 2009–2013), 2009. Internet site: www.foedevarestyrelsen.dk/SiteCollectionDocuments/25_PDF_word_filer%20til%20download/04kontor/Salmonellahandlingsplan IVtilpdf.pdf (Accessed November 2011).

De Vos, C.J., H.W. Saatkamp, and J. Ehlers. “Simulation Evaluation of *Salmonella* Monitoring in Finishing Pigs in Lower Saxony, Germany.” *Preventive Veterinary Medicine* 82(2007):123–37.

Danish Ministry of Transports and Energy. “Key Figures to be Used for Socio-economic Analysis Regarding Transports, December 2004, Revised June 2006.” (Transport- og Energiministeriet: Nøgletalskatalog-til brug for samfundsøkonomiske analyser på transportområdet, December 2004, revideret juni 2006). 2006. Internet site: http://www.trm.dk/~/media/Files/Publication/2006/Noegletalskatalog_rev_feb_2006.ashx (Accessed November 2011).

Goldbach, S.G., and L. Alban. “A Cost–Benefit Analysis of *Salmonella*-Control Strategies in Danish Pork Production.” *Preventive Veterinary Medicine* 77(2006):1–14.

Jensen, H.H., and L.J. Unnevehr. HACCP in Pork Processing: Costs and Benefits.” *The Economics of HACCP—Costs and Benefits*. L.J. Unnevehr, ed. St. Paul, MN: Eagan Press, 2000.

Jensen, H.H., L.J. Unnevehr, and M.I. Gomez. “Costs of Improving Food Safety in the Meat Sector.” *Journal of Agricultural and Applied Economics* 30,1(1998):83–94.

Jensen, T., and H. Christensen. “Dekontaminering af Svinekød. Dokumentation af Effekt ved Undersøgelser på Slagtergangen” in *Danish (Decontamination of Pork, Documentation of Effect through Investigations in the Processing Plant). Work No 18.361, Report of the 23rd August*. Roskilde, Denmark: Danish Meat Research Institute, 2000.

Krak Company and Search Engine. Internet site: www.krak.dk (Accessed July 2008).

Lawson, L.G., J.D. Jensen, P. Christiansen, and M. Lund. “Cost-effectiveness of *Salmonella* Reduction in Danish Abattoirs.” *International Journal of Food Microbiology* 134,1–2(2009): 126–32.

Malcolm, S.A., C.A. Narrod, T. Roberts, and M. Ollinger. “Evaluating the Economic Effectiveness of Pathogen Reduction Technologies in Cattle Slaughter Plants.” *Agribusiness* 20, 1(2004):109–23.

Martin, L.L. “Production Contracts, Risk Shifting, and Relative Performance Payments in the Pork Industry.” *Journal of Agricultural and Applied Economics* 29,2(1997):267–78.

Nelson, R.A. “On the Measurement of Capacity Utilization.” *The Journal of Industrial Economics* 37,3(1989):273–86.

Nielsen, B., L. Alban, L.L. Sørensen, V. Møgelmose, J. Bagger, J. Dahl, and D.L. Baggesen. “A New *Salmonella* Surveillance and Control Programme in Danish Pig Herds and Slaughterhouses.” *Berliner und Munchener Tierarztliche Wochenschrift* 114(2001):323–26.

Nielsen, B., J. Dahl, S.G. Goldbach, and H. Christensen. “Cost-Effectiveness Analysis of the Danish *Salmonella* Control Strategy.” 6th International Symposium: Safe Pork USA (2005): 83–85.

Poljak, Z., C.E. Dewey, R.M. Friendship, S.W. Martin, and J. Christensen. “Multilevel Analysis of Risk Factors for *Salmonella* Shedding in Ontario Finishing Pigs." *Epidemiology and Infection* 136(2008):1388–400.

Unnevehr, L.J., and H.H. Jensen. "The Economic Implication of Using HACCP as a Food Safety Regulatory Standard." *Food Policy* 24,6(1999): 625–35.

van der Gaag, M.A., H.W. Saatkamp, G.B.C. Backus, P. van Beek, and R.B.M. Huirne. "Cost-Effectiveness of Controlling *Salmonella* in the Pork Chain." *Food Control* 15(2004):173–80.

Veerle, H., G. Verbeke, M. Vandebroeck, and R. Geers. "Development of a Sanitary Risk Index for *Salmonella* Seroprevalence in Belgian Pig Farms." *Preventive Veterinary Medicine* 86(2008):75–92.

Vosough, A.B., A.G.J. Velthuis, H. Hogenveen, and R.B.M. Huirne. "Cost-Effectiveness of Beef Slaughterhouse Decontamination Measures in The Netherlands." *Food Economics* 3,3/4(2006):161–73.