Optimal Levels of Inputs to Control *Listeria monocytogenes* Contamination at a Smoked Fish Plant

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Selected paper prepared for presentation at the American Agricultural Economics Association Annual Meeting, Providence, Rhode Island, June 25-27, 2005

Abstract

Reducing the incidence of listeriosis from contaminated food has significant social health benefits, but reduction requires the use of additional or higher quality inputs at higher costs. We estimate the impact of three inputs in a food processing plant on the prevalence of *L. monocytogenes* contaminated finished cold smoked salmon. These three inputs were non-contamination of the raw fish fillets, non-contamination of the plant environment, and rate of glove changes on workers. We then estimate the levels of these inputs to use such that the marginal cost of these inputs become equal to the increased social health benefit of reduction in human listeriosis. Since the costs of these inputs are borne by the food processing plant, which may not be able to secure a higher product price because of asymmetric information, we show how social sub-optimal use of these inputs may result.

This paper is based upon research funded by a USDA CSREES Integrated Food Safety Initiative Grant (2003-51110-0171).

Introduction

Listeria monocytogenes causes severe illnesses resulting in high mortality. The Center for Disease Control and Prevention (CDC) estimates that approximately 2,500 cases of invasive listeriosis occur annually in the U.S., with a hospitalization rate of 92%, and case fatality rate of 20%. Most cases are believed to be linked to consumption of ready to eat foods. Reducing the incidence of listeriosis has significant social health benefits, but reduction requires the use of additional or higher quality inputs at higher costs.

One ready to eat food which can be contaminated with *L. monocytogenes* is cold smoked salmon. Although brined and smoked, to maintain consumer desired texture and taste, the temperature used in the smoking process is generally insufficient to kill *L. monocytogenes*. Further, it is believed that contamination often occurs after smoking when the fillets are sliced and packaged (Hoffman et al., and Gall et al.).

We estimate the impact of three inputs in a smoked salmon processing plant on the prevalence of *L. monocytogenes* contaminated finished smoked fish, and determine the economic optimal use of the inputs given the prices of these inputs and the social value of reducing the prevalence of *L. monocytogenes* in the finished product. These three inputs are the prevalence of non-contaminated raw fish fillets, the prevalence of non-contaminated plant environment, and rate of glove changes on workers. Successively higher quantities of these inputs are required to produce increased prevalence levels of *L. monocytogenes* free finished product. In addition, except for glove changes, the prices of these inputs increase immensely to reach higher levels of input quality. As a result, completely *L. monocytogenes* free finished product is cost prohibitive, although high level of non-contamination can be reached.

Data Generation

A multiple equation dynamic stochastic process model of the filet slicing and packaging room as reported by Ivanek et al. was used to simulate the production process to generate input and output observations. Data for this stochastic model was previously collected from the plant as reported in Lappi et al. and Ivanek et al. Data used by Ivanek et al. included the prevalence of *L. monocytogenes* contamination for raw fish and environmental samples, as well as time and motion measures. The constructed model was a difference equation system, based on the Reed-Frost model (Fine). The model also included as a variable the cleanliness of the food contact surface at the beginning of the shift, but this variable proved to be statistically insignificant in our later production function estimates. Therefore, this variable is not included in our production function, although we allow it to vary stochastically in our data simulation. Beginning cleanliness of the food contact surface does not appear to be a significant source of contamination at the levels of cleanliness observed in the plant modeled. We conclude that contamination must occur from an outside contaminant, such as the entering fish fillets, or the plant environment, and spread by gloves on the workers as supported by observations discussed by Hoffman et al.

This dynamic stochastic process model was used to generate 810 observations to estimate a production function by shifting the means of the underlying distributions to represent changing the expected values of the inputs. The output is an index of *L. monocytogenes* prevalence in the finished smoked fish fillets, bounded between zero and one, with one representing no contamination. Thus a value of “1” indicates that 100% of the product is free of *L. monocytogenes*. This specification is unconventional in that normally prevalence is in terms of contamination rather non-contamination, but our specification allows increases in the output (non-contamination) to be viewed as a positive good, with a positive and increasing price. Both the raw fillets and plant environment were also measured as bounded between zero and one, again with one being no contamination of *L. monocytogenes*. The glove change variable is measured as the number of glove changes per worker per hour, but bounded from zero to infinity.

The assumption is that the plant manager can purchase or utilize inputs of various expected non-contamination, but little or no information is known by the plant manager about the variation around that expected quality, although the actual quality, represented by a draw from the distribution, may be different from the expected value and this actual quality of the input will impact the quality of the finished product. Thus the plant buys inputs based upon expected values but receives an input that is stochastic around that expected value.

Each probability distribution for the three varied inputs where shifted by factors of 0.5, 1.0, and 1.5. These three inputs each with three values resulted in 27 different combinations. Thirty replications were performed for each combination resulting in a data set of 810 observations. A fourth control variable in the Ivanek et al. model, the beginning food contact surface contamination was left stochastic with no distribution shift. This implies that there will be no change in the expected value of that variable. Initially shifting this distribution resulted in statistical insignificant impact of that variable on expected non-contamination of the finished product.

Production Functions

The output, non-contamination prevalence, defined as the prevalence of *L. monocytogenes* non-contaminated finished products, is bounded between zero and one, with one representing no contamination. The functional forms estimated included the Cobb-Douglas, semi-log, logistic, and the inverse (hyperbola). The inverse was used in the economic analysis based upon statistic fit and functional characteristics.

The functional form for a single output, single input inverse function is:

$$y = \alpha + \beta/x, \quad \beta<0$$

where the α coefficient is the asymptotic value that y approaches as the variable x approaches infinity.

For three inputs the function is written as:

$$y = \alpha + \beta_1/x_1 + \beta_2/x_2 + \beta_3/x_3, \quad \beta_i<0$$

This function was estimated by linear least squares regression using the 810 observations with results show in Table 1. All estimated coefficients were statistically significant with negative signs on the Beta coefficients as expected. Thus, increasing the use of any of the three inputs will increase the non-contamination of *L. monocytogenes* in the final product.

Interaction terms between the three inputs were also initially included in the production function, but all estimated cross product coefficients were statistically insignificant and therefore not included in the utilized production function. With no cross product coefficients the marginal product of each input is independent of the use of the other two inputs and, thus, the productivity of each input is independent of the use of the other inputs.

A variance heterogeneity correction process was utilized in estimating the production function, using the non inverse values of the three inputs in the correction equation. Results are show in Table 1. If this variance correction is interpreted as a stochastic production function as in a Just and Pope specification, then increased levels of fish quality and increased glove changes will reduce the stochastic product quality variability and thus reduce risk. In contrast, a cleaner plant environment, although increases expected product quality, does not appear to impact product quality variability. Although the Just and Pope specification can be matched with an expected utility model to assess risk decision making, utilizing the expected and variance of product quality, that approach is not used in this article. Recent literature on risk in the firm discounts the role of expected utility as a measure of cost of risk to the firm and suggests that expected values only may be relevant (Doherty). In the analysis that follows the production function estimates are used to produce expected output values.

Table 1. *L. monocytogenes* Non-Contamination Estimated Production Function with Correction for Variance Heterogeneity

	Estimate	t-Statistic	Prob. $H_0 = 0$
Production Function Estimates			
Intercept	1.3213	15.63	0.00
Fish	-0.2048	-5.10	0.00
Environment	-0.1295	-1.97	0.05
Gloves	-0.02402	-8.68	0.00
Variance Correction			
Sigma	0.6208	1.16	0.25
Fish	-4.9702	-4.82	0.00
Environment	0.7902	0.50	0.62
Gloves	-1.1660	-6.14	0.00

The estimated expected production function is:

$$y(raw, env, glo) := 1.3213 - \frac{0.2048}{raw} - \frac{0.1295}{env} - \frac{0.02402}{glo}$$

where y is the non-contamination of *L. monocytogenes* in the finished smoked salmon product, raw is non-contamination of *L. monocytogenes* in the raw fish, env is non-contamination of *L. monocytogenes* in the plant environment, and glo is the rate of glove changes per hour per worker. The intercept is greater than one but values of the inputs over their bounded ranges will bring the finished product contamination to below one. For instance, completely clean fish, a completely clean plant environment and two glove changes per hour produces a finished product non-contamination prevalence of 0.975.

These production relationships in each of the variables are plotted in Figures 1 through 3. Figure 1 illustrates what happens to finished product non-contamination as the quality of the raw fish approaches the value of one, reflecting a contamination free input, given a completely clean environment and two glove changes per hour. Figure 2 illustrates what happens to finished product non-contamination as the quality of the plant environment approaches the value of one, given completely clean fish and two glove changes per hour. Figure 3 shows what happens to finished product non-contamination as the number of glove changes per hour per worker increases, given completely clean fish and plant environment.

Figure 1: ***L. monocytogenes*** **Non-Contamination as Raw Fish Quality Changes with Clean Plant Environment and 2 Glove Changes per Hour.**

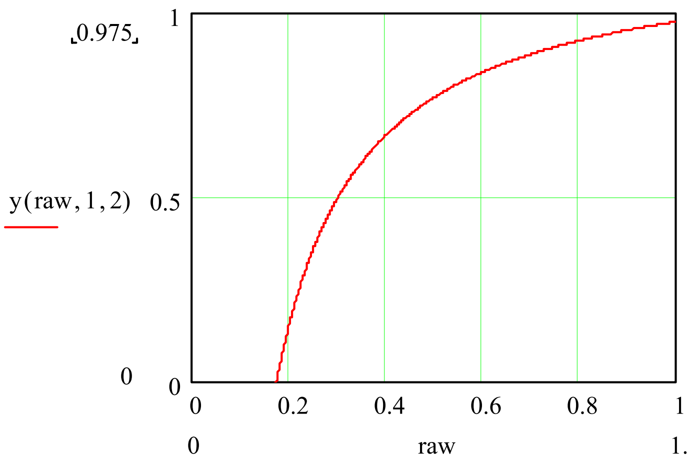
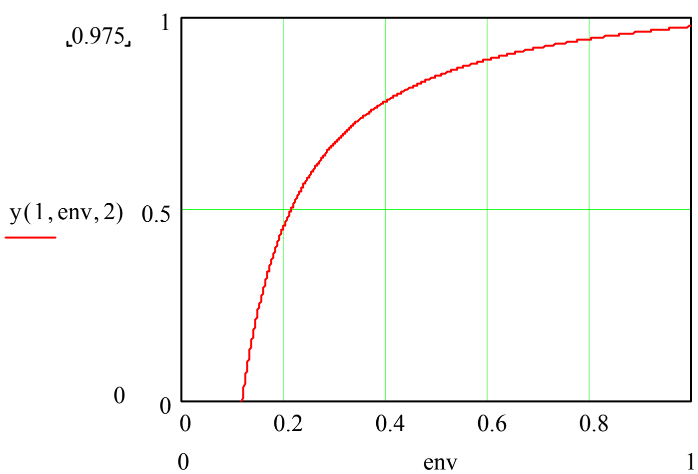


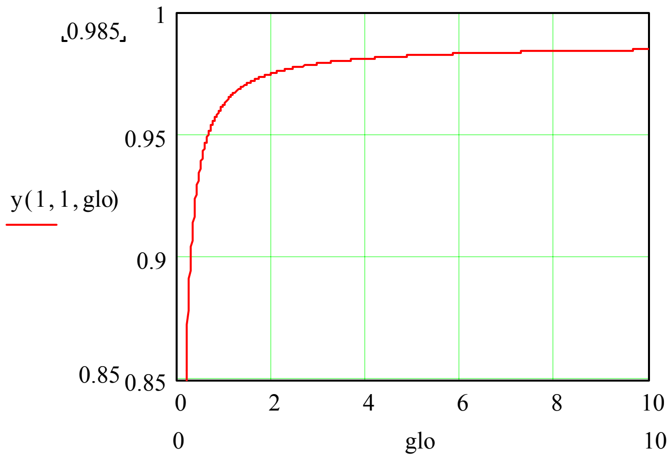
Figure 2: ***L. monocytogenes*** **Non-Contamination as Plant Environment Changes with Clean Raw Fish and 2 Glove Changes per Hour.**



Marginal Products and Elasticities

Marginal products measure how a change in an input will change the non-contamination of the final product. The marginal products of the inputs for the estimated inverse function are functions of each individual input only. Elasticities, which show the percentage change in non-contamination of the final product from a percentage change in an input are a function of all inputs, and are typically used to report the sensitivity of changes in output to changes in inputs.

Figure 3: *L. monocytogenes* Non-Contamination as Glove Changes with Clean Raw Fish and Clean Plant Environment.



At the data mean values of 0.879 for the raw fish, 0.922 for the environment, and 0.462 for the glove changes per hour, the computed elasticities of the three inputs are 0.260 for the raw fish, 0.157 for the plant environment, and 0.058 for glove changes. This means that a one percent increase in the non-contamination of the raw fish, from 0.879 to 0.888, will increase the non-contamination of the finished product 0.26 percent, or from 0.896 to 0.898. These elasticities will change for different initial values of the three inputs and as reported in Table 2.

Table 2. Output Elasticities for the Three Inputs at Various Values

Input Values			Elasticities		
Raw Fish	Environment	Gloves	Raw Fish	Environment	Gloves
0.879	0.922	0.462	0.260	0.157	0.058
1.000	0.922	0.462	0.222	0.157	0.056
0.879	1.00	0.462	0.257	0.143	0.057
0.879	0.922	2.00	0.249	0.150	0.013

Note: For comparison purposes, the constant elasticities from the Cobb-Douglas production function were 0.288 for Raw Fish, 0.156 for Environment, and 0.054 for Gloves.

Price Functions

Except for glove changes, input and output prices are not constant, but vary by quality, so we estimated non-linear price relationships using financial and test data from the plant, previous research, and expert advice. The price of successively greater levels of a clean environment becomes successively more expensive and the cost of a completely clean environment is cost prohibitive. The functional form to represent this relationship is:

$$\text{penv}(\text{env}) := \frac{1}{et_0 + et_1\left(1 - \frac{\text{env}}{1}\right)}$$

where penv is the price of the environment at different levels of environment non-contamination bounded between zero and one. This equation can be estimated with linear regression as

$1/\text{penv} = et_0 + et_1 * (1\text{-env})$

The plant modeled had implemented changes in cleaning and maintaining plant environment cleanliness that increased tested environmental quality. Samples taken before and after these changes were implemented, and the annual cost of cleaning the plant before and after changes, provides two observations to fit this function. These expenditures were divided by the annual plant production to arrive at a cost per kilogram of finished product. A third observation was included by setting the environmental variable equal to one, representing a completely clean environment, and using a large environment cost. This is a very thin data set, and with a two parameter function only provided one degree of freedom. The three observations are shown in Table 3. The estimated coefficients are in Table 4. Figure 4 graphs this price function. As can be seen the price of a successively cleaner plant increases modestly at first but then increases dramatically.

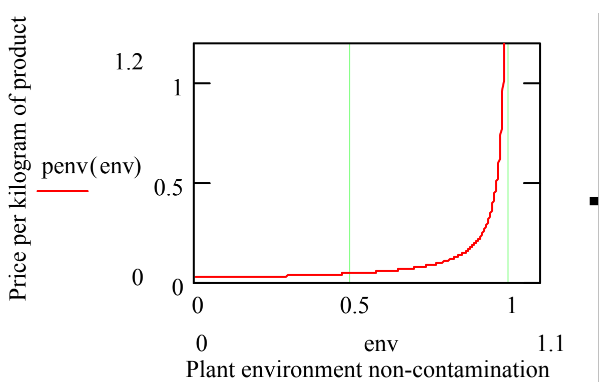
Table 3: Data to Estimate Environment Price Equation

Cost per kilogram of finished product	1/Cost per kilogram	Non-Contamination
0.0576643	17.341756	0.630
0.0874729	11.432118	0.762
10000	0.0001	1.000

Table 4: Estimated Environment Price Equation

Coefficient	Estimate	t-Statistic
et_0	0.064253	0.30
et_1	47.00858	55.84
R-Square	0.99	

Figure 4: Price Function for Plant Environment



The same functional form was used to estimate the price of fish at various levels of *L. monocytogenes* non-contamination. The current price of raw fish is $3.00 per pound or $6.078 per kilogram. Samples at the plant produced a non-contamination of 0.894, based upon packages of smoked salmon, Ivanek et al. This assumes that the contamination per kilogram of finished product corresponds to the prevalence of contaminated packages. A calcium hydroxide treatment is available (Jahnke et al.) which is estimated to cost $0.25 per pound or $0.55065 per kilogram. This treatment was projected to reduce contamination 10 fold, thus increasing non-contamination to 0.9834. A third data point represents completely contamination free raw fish at an extremely high price. These data are shown in Table 5. The estimated coefficients are show in Table 6 and the price relationship is illustrated in Figure 5.

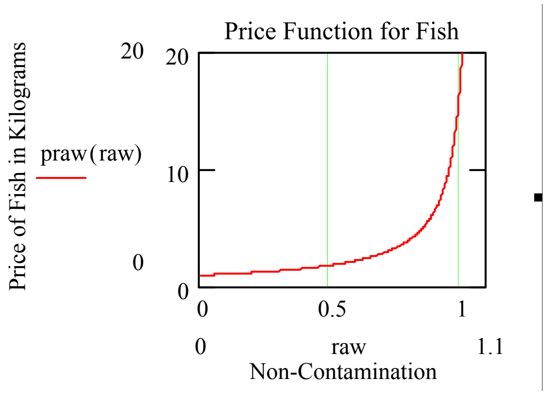
Table 4: Data for Fish Price Function

Cost per kilogram of fish	1/Cost per kilogram	Contamination
6.6078	0.1513363	0.894
7.15845	0.1396951	0.983
10000	0.0001	1.000

Table 5: Estimated Fish Price Equation

Coefficient	Estimate	t-Statistic
ep_0	0.056056	0.83
ep_1	0.9991	0.92
R Square	0.68	

Figure 5. Price Function for Raw Fish



The price of a glove change included the purchase price of a pair of gloves and the estimated time it took to change a pair of gloves multiplied by the wage rate and then divided by the quantity of fish processed, adjusting for no production during the glove change time. This resulted in an estimate of $0.04 per glove change per kilogram of finished product.

The last price relationship is the price of the finished product as a function of *L. monocytogenes* non-contamination. This relationship is expected to be increasing such that reduced contamination would command a higher social price. The functional form used was the power function, $p = \alpha * q^{\beta}$, where p is the price, q is the quality bounded between zero and one, and α and β are coefficients to be estimated. The α coefficient should be positive reflecting an increasing relationship between quality and price. A β coefficient greater than one produces a convex relationship, while a β coefficient less than one produces a concave relationship.

The current market price for smoked salmon is $44.12 per kilogram. In recent plant samples 3 of 66 finished product samples tested positive, for a non-contamination prevalence of 0.954 (Lappi, et al.). That provides one observation. Hayes et al. in an experimental economics study found respondents willing to pay 15% to 30% more for food that is essentially completely safe from 5 pathogens. This is the willingness to pay, which includes cost of illness plus averting behavior. Using the 30% level produces a price of $57.36 with a non-contamination prevalence of 1.00. Since only two observations were used with a two parameter function the regression line was exactly fitted as:

$$\log(price) = \log(a) + b * \log(prod),$$

which was transformed into it's anti-log form of:

$$price = 46.77 * prod^{1.267},$$

where price is the price of the final product and prod is the non-contamination prevalence of the final product.

Results

The levels of inputs the plant should use to maximize profits of the firm were computed using MathCad software. The three first order conditions for profit maximization were specified so that the value of the marginal product of each input was set equal to their respective price. These were solved simultaneously for the quantity of each input to use which would maximize expected profit to the plant. Except for the price of a glove change, the prices of the inputs were not constant but increase as the input increases as specified in the price functions estimated. Output price was a function of the three inputs, since input usage impacts product quality, which impacts the output price.

Previously, 66 samples from the plant produced a *L. monocytogenes* non-contamination prevalence of 0.954. Economic optimal non-contamination of the finished product computed for the plant from our economic model was higher at 0.975, which has a social a value of $49.60, which includes consumer willingness to pay to avoid food illness. This price is higher than the current market price of $44.12. At this optimality, the quality of the raw fish is 0.964 at a price of $10.92 per kilogram. The current price of raw fish is $6.61 per kilogram. The optimal plant environment non-contamination is 0.998 at a price of $6.45. This is much cleaner than current samples reflect at an exorbitant expenditure per kilogram, a hundred fold increase over current expenditure per kilogram of finished product. The optimal number of glove changes is 5.5 per hour at a price of $0.04 per glove change. The production function becomes very flat at these low incidence levels, and large quantities of inputs at successively higher prices are necessary to economically optimally reduce *L. monocytogenes* contamination. These results are based upon estimate price relationships with few data points and other price relationships will produce different optimal results.

Incomplete information for consumers on the quality of food products leads to consumers' inability to assess the quality of a food product and pay their premium for higher quality. We used a consumer premium of 30 percent for a completely clean product, which increases the market price from $44.12 to $57.36 per kilogram for completely free product. The plant has limited ability to receive a higher price for a higher quality product. To assess this limitation it is assumed that the firm would be able to extract a much lower price premium of only 1.5 percent for completely contamination free product. A new product price relationship was fitted substituting this price data point for the previous 30 percent price increase.

Optimal input usage and finished product contamination were computed using this new price relationship. Since output price increases less with quality improvement, the use of inputs fall and the non-contamination of the final product decreases. The optimal non-contamination prevalence of the finished product falls to 0.973, which is only slightly lower than the rate of 0.975 with the higher price premium. The new product price becomes $44.38, only a slight increase over the current market price of $44.12. Although the final quality does not fall much, the use of some inputs fall proportionally more since the production function is relatively flat at the optimal input levels. The new optimal quality of the raw fish is now 0.956 at a price of $9.95 per kilogram, a reduction from the previous quality of raw fish of 0.964 at a price of $10.92 per kilogram. The new optimal quality of the plant environment is now 0.997 at a price of $5.77 per kilogram, essentially no reduction from a quality of 0.998, but a price reduction from $6.45. The number of glove changes falls from 5.5 to 5.2 per hour.

Conclusions

The optimal use of three inputs which impact the prevalence of *L. monocytogenes* contamination in the finished product of a smoked fish plant were estimated using a production function and prices of the inputs and output. The single output three input production function was estimated using data generated from a previously constructed stochastic dynamic model of the filleting and packaging room of the plant. That process model was used to generate 810 observations of various stochastic combinations of the inputs and output.

The output was the prevalence of *L. monocytogenes* non-contaminated finished products. The three inputs were the prevalence of *L. monocytogenes* non-contaminated raw fish, prevalence of *L. monocytogenes* non-contaminated plant environment, and the number of glove changes per worker per hour. As these inputs increase, non-contamination of the final product increases but at a decreasing rate, approaching the value of one.

Except for glove changes the input prices were not constant but increased with greater levels of non-contamination. The value of the final product also increased with greater levels of non-contamination. These price relationships were estimated with limited number of data observations.

Economic optimal *L. monocytogenes* non-contamination of the finished product computed for the plant from our economic model was 0.975. Previous plant samples produced a non-contamination prevalence of a lower 0.954, which implies that given the estimated production function and estimated price relationships it would be optimal to produce a finished product with lower incidence of *L. monocytogenes*. This result assumes that the higher social value for the lower non-contamination can be collected by the plant by a higher price. If only a small portion of the value of non-contamination can be collected from an increased market price then the optimal non-contamination prevalence falls to 0.973, which is only slightly lower than the optimal when the social value of increased non-contamination can be collected by a higher market price for the product.

These results are unique to the estimated relationships, which are based upon data from only one plant and with price relationships estimated from thin data, so results must be interpreted with caution. The results do imply that further progress on non-contamination may be warranted even when the market does not pay the full value of the reduction on non-contamination, but that it is cost prohibitive to produce completely *L. monocytogenes* free smoked salmon finished product.

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