Modelling Traceability in the Dairy Industry

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Abstract

Traceability is the capability to trace goods throughout the distribution chain. Traceability has become an increasingly important research area in recent years. It has always been an important aspect of production, but recent contamination events have highlighted its significance. The Fonterra botulism scare of 2013 in particular exposed a need for fast accurate product tracing in the New Zealand Dairy industry.

We present a Markov chain model for the flow of milk through the early stages of the dairy supply chain. The state of the Markov chain is the value of product at each location in the production chain, in this case the milk tanker, factory reception or processing.

The model incorporates parameters for product testing and tracing upon arrival in each state of the model. By varying these parameters we are able alter the precision of the traceability system, and gain an understanding of where and when traceability has the greatest impact. By analysing the results of simulations under various scenarios we are able to estimate the value traceability can contribute to the output of the production chain.

1 Introduction

Traceability is the capability to trace goods throughout the distribution chain (Tamayo, Monteiro, and Sauer 2009). The aim of a traceability system, is to collect information relevant to the location of products along the supply chain (Dabbene and Gay 2011), allowing the flow of material to be followed(Karlsen et al. 2013). In the event of a product contamination or other fault, traceability becomes crucial. Traceability makes recalls possible (Tamayo, Monteiro, and Sauer 2009), with no traceability it is difficult to determine how far a contamination has gone, necessitating a widespread recall and the very real possibility of contaminated product being consumed by the public. The precision of a traceability system is important. It can determine how much product is recalled and the value lost (Dabbene and Gay 2011), as well as the time an effort required to locate all of the faulty product. Fast efficient location allows for reduced spread and therefore a reduced impact on consumer confidence. Good traceability is not about reducing the probability of a contamination event, but about reducing the consequences if contamination does occur (Dupuy, Botta-Genoulaz, and Guinet 2005).

It can be difficult to estimate the value of a traceability system, the return is essentially the loss avoided in the case of a contamination or other production fault (Dupuy, Botta-Genoulaz, and Guinet 2005). A model for the flow of milk from the farm to the factory is developed by Welsh, Marshall and Noy in 2016, using Markov chains to simulate dairy production under different testing conditions and various rates of product rejection. In this paper we incorporate traceability effects into the model to investigate their effect, and the costs and benefits associated with them.

2 Dairy Product Flow DTMC Model with Traceability

Based on the Multi-Event model developed in Welsh et.al.x we develop our Multi-Event model incorporating new terms and probabilities relevant to traceability. Table 1 summarises the parameters we will use in this model. A brief reasoning behind each parameter value is given in the appendix.

2.0.1 The Milk Tanker

The milk tanker stage is very similar to that presented in Welsh et.al.(Welsh, Marshall, and Noy 2016), except for the introduction of a cost associated with traceability. There are four possible activities that a tanker can undertake, one at a time. They are; Milk collection, Milk rejection, Milk delivery, or Transporting.

$$p_{ij}(\Delta t) = \begin{cases} \alpha\Phi\left(1-\frac{T(t)}{N_T}\right)\Delta t & j = i + V - E_T - L_T \quad \text{Collection} \\ (1-\alpha)\Phi\left(1-\frac{T(t)}{N_T}\right)\Delta t & j = i - E_T \quad \text{Rejection} \\ \frac{\mathcal{X}T(t)}{N_T}\left(1-\frac{F(t)}{N_F}\right)\Delta t & j = i - C_T \quad \text{Delivery} \\ 1-\left[\Phi\left(1-\frac{T(t)}{N_T}\right)+\mathcal{X}T(t)\left(1-\frac{F(t)}{N_F}\right)\right]\Delta t & j = i \quad \text{Transporting} \\ 0 & \quad \text{Otherwise} \end{cases} \tag{1}$$

Milk collection can only occur if no 'fast' test results come back with an unsatisfactory result. The probability a milk collection is attempted is dependent on the amount of milk already contained in the tanker stage.

The Probability of delivery is dependent on both the value in the tanker stage and the value in the factory reception stage.

2.0.2 The Factory Reception Stage

Fonterra has 33 processing sites around the country (Fonterra Co-operative Group). As with the tankers we will be treating these as part of the factory reception pool but each site receives and passes product on individually.

The possible events in the factory reception stage are collection, rejection, passing on for processing, or holding. Including traceability effects means this stage has two

Table 1: A Summary each parameter used in out model and its units. Frequencies are represented by the capital Greek letters $\Phi, \mathcal{X}, \Psi$ and Ω. Probabilities are represented by lowercase Greek letters. Testing costs are represented by an E with a subscript for the associated stage, similarly for the traceability costs using an L. The vat value, given by V uses units appropriate to the particular model simulation. *Denotes parameters that are new in our model.

Parameter	Description	Value	
V	Amount of Milk collected from an on-farm vat	\$3050	
Φ	Frequency of collection attempts	11970	attempts per day
$\mathcal{X}$	Frequency of delivery to factory	3990	deliveries per day
Ψ	Frequency with which milk enters processing	343	Silos per day
Ω	Frequency of process exit	7100	Units per day
E_T	Cost of testing milk at collection site	\$0.30	
L_T^*	Cost of tracing collected milk	\$0	
E_F	Cost of testing milk upon delivery	\$1.50	
L_F^*	Cost of tracing accepted milk	\$0	
D_F	Cost of disposing of unwanted milk	\$0	
E_P	Cost of testing prior to processing	\$1.50	
L_p^*	Cost of tracing milk accepted for processing	\$0	
D_p	Cost of disposing of unaccepted silo milk	\$0	
α	Probability of Type I Vat acceptance	0.9999	
β	Probability of Type I Tanker acceptance	0.99	
γ	Probability of Type I Silo acceptance	0.99999	
η^*	Probability of Type II Vat acceptance	1	
θ^*	Probability of no Type II rejection at processing entry	1	
ς	Probability of Partial Type I Tanker acceptance	0.7425	
ϖ^*	Probability of Partial Type II Tanker acceptance	1	
ϱ^*	Probability of Partial Silo acceptance	0.99999	
λ^*	Tanker Traceability coefficient	1	
ε^*	Mixing error for a tanker load in a reception silo	\$42820.80	
C_T	Average capacity of one milk tanker	\$10705.20	
N_T	Total capacity of entire milk tanker fleet	\$5620230	
C_F	Reception silo capacity	\$89000	
N_F	Total Factory reception stage capacity	\$8811100	
C_p	Processing unit capacity	\$561755	
N_p	Total Processing capacity	\$18537830	

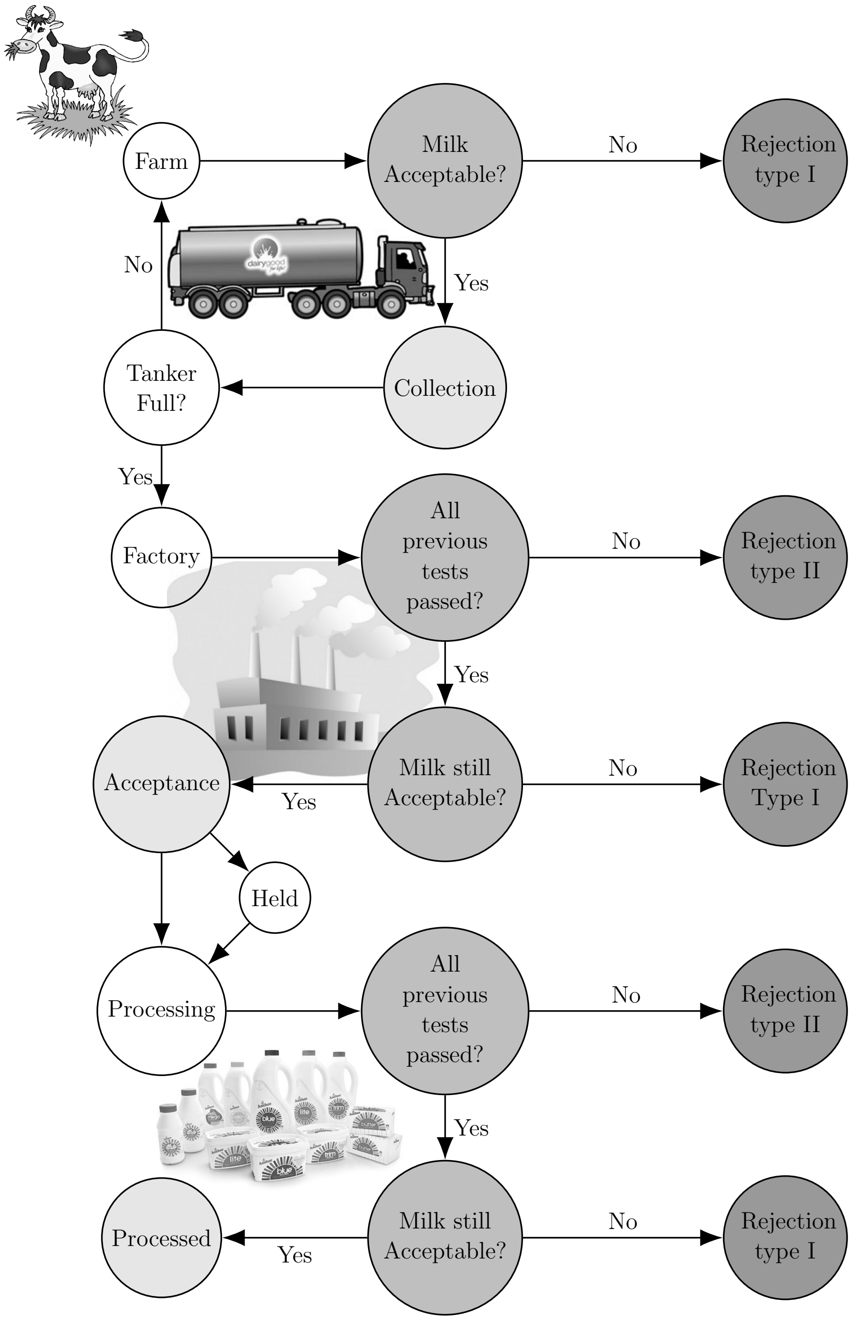

Figure 1: Flow chart, showing the path milk takes from the farm to the factory and the decisions that are made along the way.

possible rejection scenarios. If milk is rejected due to previous test results, this is a Type II rejection. There is no testing cost associated with a Type II rejection. There is now however, a disposal cost associated with the rejection of a delivery. In the rejection type I scenario, the milk is rejected due to tests done upon the tanker's arrival at the factory. The cost of the test E_F is lost along with the disposal cost D_F.

Each milk tanker has both a trailer and a truck compartment. If these two compartments can be kept separate they can be accepted and rejected separately.

Figure 2 shows a probability tree for how the probability of each acceptance and rejection combination can be calculated. We end up with three main possibilities;

total acceptance, partial acceptance or total rejection. Introducing traceability gives us many more pathways compared with those presented in Welsh et.al.

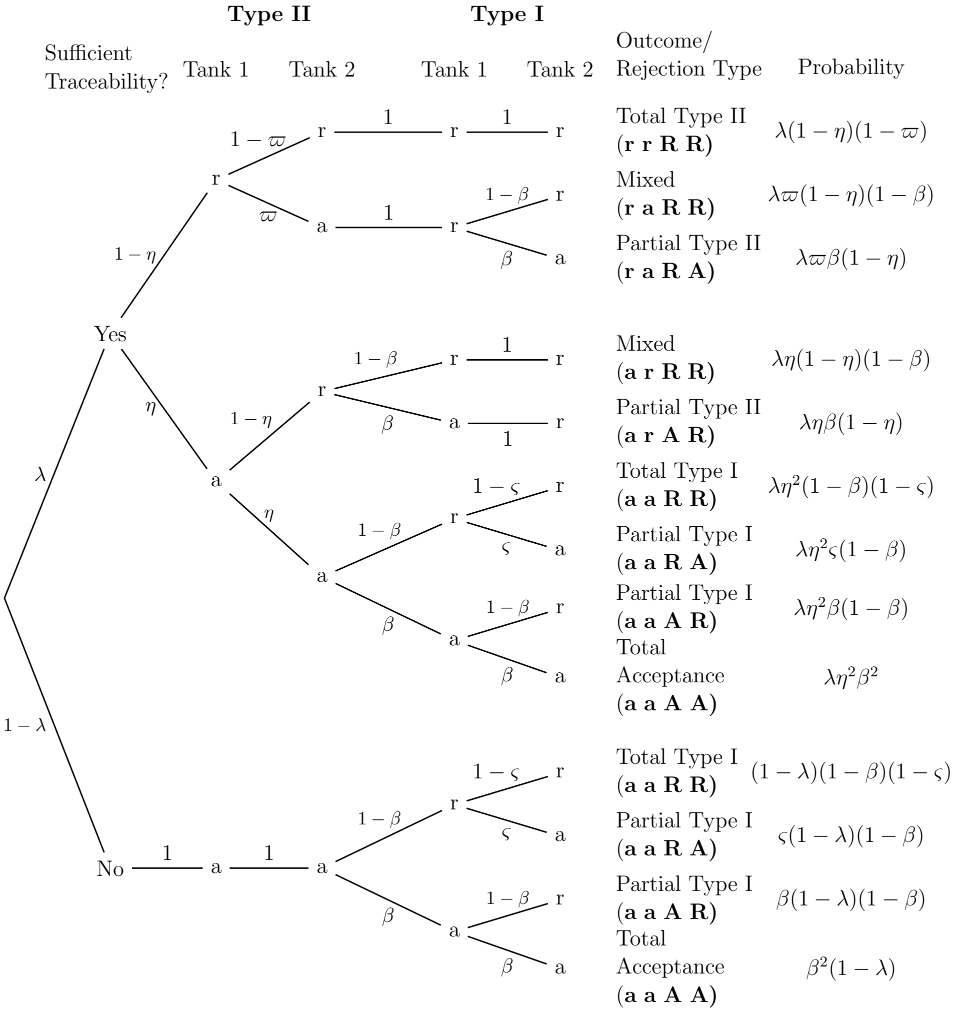

Figure 2: Probability tree showing the possible outcomes when milk is delivered to the factory. r denotes the rejection of a tanker compartment, while a denotes its acceptance up to that point.

The probability that a tanker compartment is contaminated is not totally independent of the other compartment's status. There is the possibility that some milk from one of the farms, ends up in each compartment.

$$p_{uv}(\Delta t) =$$

$$\begin{cases}
\beta^2(\lambda\eta+1-\lambda)\dfrac{\mathcal{X}T(t)}{N_T}\left(1-\dfrac{F(t)}{N_F}\right)\Delta t & v = u + C_T - E_F - L_F & \text{Acceptance} \\
(1-\beta)(\varsigma+\beta)(\lambda\eta+1-\lambda)\dfrac{\mathcal{X}T(t)}{N_T}\left(1-\dfrac{F(t)}{N_F}\right)\Delta t & v = u + \dfrac{C_T}{2} - E_F - D_F - L_F & \text{Partial Rejection I} \\
\lambda\beta(1-\eta)(\varpi+\eta)\dfrac{\mathcal{X}T(t)}{N_T}\left(1-\dfrac{F(t)}{N_F}\right)\Delta t & v = u + \dfrac{C_T - E_F}{2} - D_F - L_F & \text{Partial Rejection II} \\
(1-\beta)(1-\varsigma)(\lambda\eta+1-\lambda)\dfrac{\mathcal{X}T(t)}{N_T}\left(1-\dfrac{F(t)}{N_F}\right)\Delta t & v = u - E_F - D_F & \text{Rejection I} \\
\lambda(1-\eta)(1-\varpi)\dfrac{\mathcal{X}T(t)}{N_T}\left(1-\dfrac{F(t)}{N_F}\right)\Delta t & v = u - D_F & \text{Rejection II} \\
\lambda(1-\eta)(1-\beta)(\varpi+\eta)\dfrac{\mathcal{X}T(t)}{N_T}\left(1-\dfrac{F(t)}{N_F}\right)\Delta t & v = u - \dfrac{E_F}{2} - D_F & \text{Mixed Rejection} \\
\dfrac{\Psi F(t)}{N_F}\Delta t & v = u \ - C_F & \text{Passing on} \\
1 - \left[\dfrac{\mathcal{X}T(t)}{N_T}\left(1-\dfrac{F(t)}{N_F}\right) + \Psi F(t)\right]\Delta t & v = u & \text{Holding}
\end{cases} \tag{2}$$

$$\text{Where } \lambda = \begin{cases} 1 \text{ for } L_T \geq z \\ 0 \text{ for } L_T < z \end{cases} \tag{3}$$

2.0.3 Initial Processing Stages: Seperation and Standardisation

Similar to the Factory reception stage the possible activities include collection, rejection, and passing on, but instead of just holding product, this is time spent in production. In this part of the model we also have two types of rejection and both result in a disposal cost. Only rejection type I incurs a testing cost, as rejection type II rejection is dependent on previous tests.

At this stage of the production chain, the precision of the traceability system can determine how much product is lost in the case of a contamination. Figure 3 shows a probability tree for the possible outcomes when milk enters this stage.

Equation 4 shows the transition probabilities for this production stage

$$p_{gh}(\Delta t) = \begin{cases}
\theta\gamma\Psi F(t)\Delta t & h = g + C_F - E_P - L_P & \text{Acceptance} \\
\mu\varrho(1-\theta)\Psi F(t)\Delta t & h = g + \ell\left(C_F - \dfrac{C_T+\varepsilon}{1+\lambda}\right) & \\
 & \quad - E_P - L_P - (1-\ell)D_P & \text{Partial Acceptance} \\
\theta(1-\gamma)\Psi F(t)\Delta t & h = g - E_P - D_P & \text{Rejection I} \\
(1-\theta)(1-\mu)\Psi F(t)\Delta t & h = g - D_P & \text{Rejection II} \\
\mu(1-\theta)(1-\varrho)\Psi F(t)\Delta t & h = g - D_P - E_P & \text{Retest \& Reject} \\
\Omega P(t)\Delta t & h = g - Q & \text{Passing on} \\
1 - [\Psi F(t) + \Omega P(t)]\Delta t & h = g & \text{Producing}
\end{cases} \tag{4}$$

$$\text{Where } 0 \leq \ell = \frac{L_F}{L_F^*} \leq 1 \text{ and } \mu = \begin{cases} 0 & \text{for } \ell\left(C_F - \frac{C_T+\varepsilon}{1+\lambda}\right) \leq E_P + L_P \\ 1 & \text{for } \ell\left(C_F - \frac{C_T+\varepsilon}{1+\lambda}\right) > E_P + L_P \end{cases} \tag{5}$$

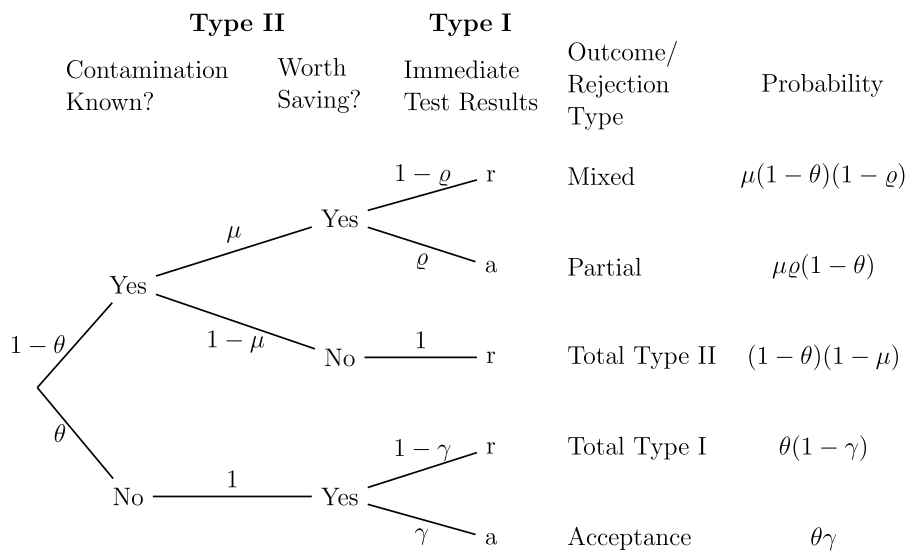

Figure 3: This probability tree shows the probability of each outcome when passing product from the factory reception stage to processing.

3 Simulation Results and Discussion

In this section we will compare the simulation results in Welsh et.al.(Welsh, Marshall, and Noy 2016) with our own simulations using traceability effects. The aim is to reduce losses resulting in overall increased product output. In comparing the simulations we will obtain a value for certain levels of traceability, given that the desired affect is achieved.

If traceability is perfect, then the location of any unit of product is always known perfectly at any point in time. This means in the event of product rejection only product likely to be contaminated is rejected. For our simulations in this section, if we invest in traceability it is perfect traceability.

Out of the three stages analysed in the model, Welsh et.al.found the acceptance rate of product when it is delivered to the factory reception to have the biggest impact on total production.

Table 2 summarises the results of several simulations. The initial type rejection rate is transferred via traceability to allow type II rejection instead. The minimum rate of type 1 acceptance needed to make this investment in traceability have a positive impact is shown along with the potential value gained if all contaminated product can be identified before Factory reception testing takes place. We use the 95% confidence intervals to determine consistent value improvement.

We can see that as the initial Type I acceptance rate increases, the potential for improvement is reduced. This makes sense as obviously there is less room for improvement. Even though the percentage of potential improvement decreases, the overall all output value still increases. There remains, however, potential for production improvement via traceability even when the rejection rate is only 1% to begin with.

Table 2: This table summarises the total 24 hour output results both before and after the introduction of traceability leading up to the factory reception stage. After the introduction of traceability the minimum type I acceptance rate for output improvement over the pre traceability scenario is given, along with the potential improvement if Type I rejection were to be eliminated.

No traceability		With Traceability		
Initial β	24 Hour Output Value	Minimum New β	Potential Gain 24 Hour Value	% Gain
0.75	\$20,144,014	0.93	\$1,902,164	9.4%
0.8	\$21,352,034	0.94	\$1,561,426	7.3%
0.85	\$22,592,592	0.96	\$1,377,442	6.1%
0.9	\$23,933,756	0.95	\$908,446	3.8%
0.95	\$25,177,680	0.99	\$576,708	2.3%

Table 3: This table summarises the total 24 hour output results both before and after the introduction of perfect traceability in the factory reception stage, affecting rejection rates in the processing stage. After the introduction of traceability the minimum type I acceptance rate for output improvement over the pre traceability scenario is given, along with the potential improvement if Type I rejection were to be eliminated.

No traceability		With Traceability		
Initial γ	24 Hour Output Value	Minimum New γ	Potential Gain 24 Hour Value	% Gain
0.75	\$21,567,212	0.86	\$2,575,236	11.9%
0.8	\$22,568,772	0.9	\$2,012,378	8.9%
0.85	\$23,600,896	0.93	\$1,435,786	6.1%
0.9	\$24,516,822	0.95	\$979,506	4%
0.95	\$25,426,016	0.98	\$566,984	2.2%

Investigation the stage separately we found greater variation in for improvement upon entry to the processing stage. The potential for improvement increases much faster as the initial acceptance rate decreases. This may in part be due to the need to gather information from each of the preceding stages in order to achieve perfect traceability precision by the time the product reaches processing, even if that information is not used until this point.

While we see large improvements in production value with the introduction of traceability effects in cases where the rejection rate would have been high, such rejection rates are not typical of everyday dairy production. Milk tanker deliveries are generally accepted 99% of the time, while processing entry has a higher acceptance rate of 99.999%. The traceability system that is used needs to react to contamination scares and minimise their impact, while not influencing day to day production negatively. As seen in the simulation results above there is potential, for even day to day production to be improved through traceability.

We see also a larger improvement due to traceability when we apply it across multiple stages of the supply chain. As shown in table 5 the effect of traceability

Table 4: This table summarises the total 24 hour output results both before and after the introduction of perfect traceability leading up to both the factory reception and processing stage. After the introduction of traceability the minimum type I acceptance rate for output improvement over the pre traceability scenario is given, along with the potential improvement if Type I rejection were to be eliminated.

No traceability		With Traceability		
Initial	24 Hour	Minimum	Potential Gain	
β and γ	Output Value	New β and γ	24 Hour Value	% Gain
0.75	$15,969,426	0.88	$4,322,318	27.1%
0.8	$17,924,698	0.91	$3,603,116	20.1%
0.85	$19,980,202	0.94	$2,805,000	14%
0.9	$22,052,910	0.96	$2,019,974	9.2%
0.95	$24,299,154	0.98	$1,037,102	4.3%

Table 5: This table summarises the total 24 hour output results both before and after the introduction of perfect traceability leading up to both the factory reception and processing stage. After the introduction of traceability the minimum type I acceptance rate for output improvement over the pre traceability scenario is given, along with the potential improvement if Type I rejection were to be eliminated.

applied at all both the factory reception and processing stages is greater than the sum of their effects individually. The potential for improvement still drops off quite steeply as the initial acceptance rate increases, though this is to be expected.

4 Conclusions

We have extended the model developed in Welsh et.al.to include traceability effects. Using this model, we investigated the impact of traceability in several different scenarios. We have shown there is significant value to be gained when we allow increased product loss via traceability, if this means we can reduce Type I rejection rates. We have also shown there is potential for output value to be improved even in the absence of significant loss events such as contamination scares.

Separately, traceability has a larger impact at the processing entry stage. The largest impact however is seen when traceability effects are applied across all the stages of out model.

A Appendix

A.1 Traceability Parameters

All parameters, unless otherwise stated, have the value given in Table 1. Parameters with new default values in this scenario are described below.

E_T This is the estimated cost of testing milk when its collected by the tanker. The Fonterra supplier's handbook lists at least 9 contamination types to be tested for along with with general quality grading and organoleptic assessment, though only two of these tests are conducted upon tanker collection every time. Based on this information we will estimate $E_T = \$0.30$ NZD.

α is the probability that the milk passes all testing and is accepted by the tanker. Vat acceptance rates suggest we set $\alpha = 0.9999$.

E_F is the cost of testing milk as it arrives at the factory. Using the earlier test cost estimate we estimate $E_F = \$1.50$.

β is the probability that a tanker load is accepted by factory. This is the stage with the greatest rate of rejection, with 1% of milk being discarded upon arrival at the factory. This means $\beta = 0.99$.

ς is the probability the second tank of a tanker will be accepted, given that the first tank was rejected. Based on the number of farms visited by each tanker, there is about a 1 in 4 chance that the contaminated load spans both tanks. Taking this into account along with the possibility there is a second unrelated contamination we can estimate $\varsigma = 0.75\beta = 0.7425$

D_F Depending on the reason for rejection, most rejected milk can be used as calf feed or sprayed on crops as fertiliser. Fonterra does contract tankers from outside their own fleet to transport this rejected milk, but the associated costs can generally recouped in the price paid for this rejected product. Because of this we set $D_F = 0$.

E_P Assuming the range of tests conducted pre-processing is similar to those conducted before acceptance into the factory, we set $E_P = \$1.50$

γ The rate of rejection before entry into the processing stage is the lowest of the three stages. Once the milk is inside the factory the environment is much more controlled, the potential for contamination or spoilage is greatly reduced. We set the chance of rejection at 0.00001%, implying $\gamma = 0.99999$.

D_P As discussed in reference to D_F, disposal cost is negligible so we can set $D_P = 0$.

λ is the traceability coefficient. It represents whether we have sufficient traceability to distinguish between tanks on a tanker or not. In this scenario we can distinguish between tanks, therefore $\lambda = 1$.

η is the probability that a tank load of milk is not rejected by a type II rejection upon delivery to the factory. This is essentially a delayed rejection of farm vats and the rejection rate reflects that. $\eta = 0.9999$

ϖ represents the conditional probability that the second tank is accepted given the first tank of the tanker is rejected by a type II rejection. Because we have perfect traceability, the second tank will only be rejected if milk from contaminated farm vat was loaded into both tanks. Each tank on the tanker holds milk from about 1- 4 farms, or an average of 1.8 based on our current parameters. So there is about a 1 in 4 chance that the contaminated load is the load spanning both tanks. Therefore, with perfect traceability the second tank can be accepted in 3 out out of 4 situations. So we let $\varpi = 0.75\eta$.

θ is the probability that a Factory reception silo does not have its contents rejected all by a type II rejection. θ reflects the value of β and that of α with $\theta = 0.95$.

ϱ is the probability that product leftover following a partial rejection is accepted following retesting. A partial acceptance can only take place in a type II rejection situation. Therefore, in a perfect traceability scenario $\varrho = \gamma = 0.99999$.

ℓ determines what portion of a contaminated silo can potentially be accepted based on the level of traceability employed in the factory reception stage. Because we have perfect traceability in this scenario $\ell = 1$.

ε This represents the mixing of milk in the reception silo, and the amount either side of a contamination that must be rejected along with the contaminated tank volume. Because milk is liquid this value is relatively large, We will set this at $\varepsilon = 4C_T = \$42820.8$

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