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A STOCHASTIC MODELING PROCEDURE FOR PREDICTING THE TIME OF CALVING IN CATTLE

Thi Thi Zin[1,*], Kosuke Sumi[1], Pann Thinzar Seint[1], Pyke Tin[1]
Ikuo Kobayashi[2] and Yoichiro Horii[3]

[1]Graduate School of Engineering
[2]Field Science Center, Faculty of Agriculture
[3]Center for Animal Disease Control
University of Miyazaki
1-1 Gakuen Kibanadai-nishi, Miyazaki 889-2192, Japan
{ horizon0125; pannthinzarseint; pyketin11 }@gmail.com; { ikuokob; horii }@cc.miyazaki-u.ac.jp
*Corresponding author: thithi@cc.miyazaki-u.ac.jp

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Abstract. *In this paper we introduce a stochastic modeling technique for predicting time to the occurrence of calving events in cattle. Specifically we establish an application procedure of Wald's fundamental identity in sequential analysis to predict the time to dairy cow calving as accurately as possible. We have well recognized that Wald's identity is a fairly handy tool for studying the properties of random walks arising in queueing and dam theories and many other stochastics processes. The identity enables us to obtain absorption probabilities of random walks with one or more barriers which can be interpreted as the occurrence of a calving event in cattle. In order to investigate the proposed problem more insight, we consider the activities of a pregnant cow around the calving event as a sequence of random variables forming a random walk. We then derive results for predicted calving times at which an individual cow calving event occurs in a video-monitored maternity barn. For experimentations, two special probability distributions parameterized by using some real-life data are utilized. The outcome results show the proposed method is promising with high accuracy.*
Keywords: Wald fundamental identity, Random walk model, Special probability distributions, Counting process of geometric type and Poisson type, Cow activities sequences, Calving time prediction

1. **Introduction.** An accurate prediction of calving time is a central to a good reproductive farm management system which leads to precision dairy farming. At this point, farmers only estimate when calving is bound to happen: expected calving is roughly between 267 and 295 days after insemination [1]. However, several researchers have investigated to predict calving time events by using video images and wearable devices [2-5]. In this concern, various methods have been developed such as machine learning techniques [6], Markov chain approach [7], random walk models [8] and empirical studies [9], to name a few. More recently, some authors showed that a combination of data from sensors detecting cumulative activity, rumination activity, feeding activity, and body temperature improved the accuracy of the prediction of the time of calving process initiation, compared to a prediction based only on the date of the insemination [10]. However, the prediction of the specific calving start time is still difficult. According to the available literature, prediction systems based on behavioral indicators seem the most promising because significant changes of behaviors can be observed within the day of calving. Moreover, a sizable number of researchers have investigated these significant changes starting from several days before delivery until the time of calving event occurs. Among many

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others, behaviors of searching for isolation, tail movements, aimless walking, decrease in rumination time, reducing of lying time, and frequent change in posture are significantly observed [5,11-15]. In general, these changes in behaviors around the calving event indicate key points for calving time prediction. The aim of this paper is to explore and examine a calving time prediction model by using the concept of stochastics modeling techniques which have been very successful in queuing theory, water storage models and inventory control [16,17]. Recently, the feasibility of the practical application of the sequential analysis method decision that has appeared in the literature has been explored [18]. According to the findings of [18], the sequential methods allow to justify the choice of metric measures depending on particular distributions which in our case are geometric and Poisson so that it makes our proposed method valid. A similar conclusion may be drawn from the findings of [19].

The major contributions of this paper are:

(i) To show how powerful the Wald's Fundamental Identity in sequential analysis could be extended to its horizon widen up to dairy science application areas;

(ii) To illustrate utilizations of some simple particular distributions, the important problem of calving time prediction in modern dairy farming systems could be dealt with only by using a few available data;

(iii) To demonstrate how accurate the proposed method has achieved by using actual collected data from a large dairy farm.

The rest of the paper is organized as follows. Section 2 describes materials and method including data collection, calving prediction model and detailed computational procedures. Then some experimental results and discussions are shown in Section 3, by using real life datasets. Finally, in Section 4, the concluding remarks are presented.

2. Materials and Methods.

2.1. **Data collection and data preparations.** In order to collect posture changes of a pregnant cow a few days prior to the occurrence of the actual calving event, we set up a 360-degree camera from overhead location of cow calving ban. We can then have the positions and states of cows that may appear in different views of 360-degree camera and all cows are clearly visible from overhead to identify cow states. A sample camera view for calving ban is shown in Figure 1. By applying image processing techniques, it has analyzed the four states of cow movements such as Standing, Lying, Standing-to-Lying

Figure 1. The camera view of cow calving ban

and Lying-to-Standing [7,18,19]. In this paper, we shall utilize only transitional posture changes during three days prior to calving event. An hourly count of posture changes is recorded and described as a sequence of random variables X_t with a time index t for $t = 1, 2, \ldots, n$ hours. In our case, since we have collected the data during three days prior to calving event, it can be seen $n = 72$ hours. In order to establish a prediction model for the occurrence of calving event, we assume the sequence of these random variables obeys a certain probability distribution. Specifically, we shall consider two common distributions, namely (i) geometric distribution and (ii) Poisson distribution with parameters derived from the collected data. As an illustration, we have collected hourly counts of the number of posture changes for 25 pregnant dairy cows three days prior to actual calving time taken place. We then calculate the sample mean of those counts for 48 hours and fit into two distributions. The calculated sample distributions are shown in the following equations.

(A) Geometric Distribution. *Consider a sequence of hourly posture changes from the geometric distribution for instance,*

$$p_j = Pr\{X_t = j\} = pq^j \tag{1}$$

where $j = 0, 1, 2, \ldots$, $0 < p < 1$ and $q = 1-p$. The probability generating function $(p.g.f)$ of X_t is then given by

$$G(z) = \sum_{j=0}^{\infty} pq^j z^j = \frac{p}{1 - qz} \tag{2}$$

We can easily show that the mean of the distribution (1) is

$$mean = m = q/p \tag{3}$$

By using the normalized equation $p + q = 1$, we obtain

$$p = 1/(1 + m) \text{ and } q = m/(1 + m) \tag{4}$$

In our case, from the collected data, as a sample, for cow ID 2, $m = 0.791667$, $p = 0.55814$ and $q = 0.44186$.

(B) Poisson Distribution. *Now we consider the case where the sequence of cow activity changes has the Poisson distribution with mean, μ:*

$$p_j = Pr\{X_t = j\} = e^{-\mu}\frac{\mu^j}{j!} \tag{5}$$

where $j = 0, 1, 2, \ldots$. The probability generating function $(p.g.f)$ of X_t is then given by

$$G(z) = \sum_{j=0}^{\infty} e^{-\mu}\frac{(\mu z)^j}{j!} = e^{-\mu(1-z)} \tag{6}$$

In the case of collected cow data, we have for cow ID 2, $\mu = 0.791667$.

We shall utilize these stated distributions along with collected data to predict the time for calving events.

2.2. **Prediction model preparations.** As a preparation for calving time prediction model, we first consider the fundamental identity of Wald in sequential analysis. The identity and its extensions had been successfully applied in stochastic reservoir theory. Briefly, the fundamental identity is described as follows.

Let $X_1, X_2, X_3, \ldots$ be independent and identically distributed random variable with finite mean and N is random variable taking valuables in the positive integers such that N is independent of $(X_1, X_2, X_3, \ldots)$ and $E(N) < \infty$. We then observe that the partial sum $S_N = X_1 + X_2 + \cdots + X_N$ behaves as a random walk that satisfies the following identity generally known as Wald's fundamental identity:

$$E\left[e^{\theta S_N}(M(\theta))^{-N}\right] = 1, \text{ where } M(\theta) = G\left(e^{\theta}\right)e^{-\theta} \tag{7}$$

where N is such that $S_N >= b$ or $S_N <= a$ while $a < S_n < b$ for all $n < N$. By using probability theory and mathematical analysis, it can be proved that there exists one and only one real root $\theta_0 \neq 0$ such that

$$M(\theta) = G\left(e^{\theta}\right) e^{-\theta} = 1 \tag{8}$$

Substituting $\theta = \theta_0$ in Equation (7), we then have

$$E\left[e^{\theta_0 S_N}\right] = 1 \tag{9}$$

We shall utilize Equation (9) to derive the predicted time to calving with high accuracy.

2.3. **Computational procedure calving time prediction.** Let us recall the sequence of hourly posture changes X_t for $t = 1, 2, \ldots$, and the partial sum $S_N = X_1 + X_2 + \cdots + X_N$. Many previous researches have indicated that the frequency of posture changes is significantly higher around the time of calving. Thus, without loss of generality we can assume that the partial sum reaches at a certain level say K, the calving event occurs if it starts with a value x.

Let us now denote the probability that the partial sum reaches at level $K - x$ by $P(x)$. We then have from Equation (9) that

$$P(x)e^{(K-x)\theta_0} + (1 - P(x))e^{-x\theta_0} = 1 \tag{10}$$

It reduces to

$$P(x) = \frac{1 - e^{x\theta_0}}{1 - e^{K\theta_0}} = \frac{1 - (\lambda_0)^x}{1 - (\lambda_0)^K} \tag{11}$$

where $\lambda_0 = e^{\theta_0}$.

This will be a probability of calving when we start at x for $x = 1, 2, \ldots, K$.

$$\text{If } \lambda_0 = 1, \text{ then } P(x) = x/K$$

We can also see that λ_0 is the unique root (other than unity) of the equation.

$$G(z) = z \tag{12}$$

where the probability generating function of the sequence random variables X_t is $G(z)$.

Thus, by using the fundamental concept of probability theory, the time taken to have the calving event with starting state x is given by

$$T_x = 1 \Big/ P(x) = \frac{1 - (\lambda_0)^K}{1 - (\lambda_0)^x}, \text{ for } x = 1, 2, \ldots, K \tag{13}$$

Thus, finally we obtain the predicted time taken for the occurrence of calving event is

$$T = T_1 + T_2 + \cdots + T_k \tag{14}$$

For implementation, we shall consider two cases of posture changes distributions, namely geometric and Poisson distributions.

In the case of geometric distribution, λ_0 satisfies the following equation.

$$G(z) = \sum_{j=0}^{\infty} pq^j z^j = \frac{p}{1 - qz} = z \tag{15}$$

Also, when the sequence is Poisson distribution, we have λ_0 as the unique solution (rather than unity) of Equation (15).

$$G(z) = \sum_{j=0} e^{-\mu} \frac{(\mu z)^j}{j!} = e^{-\mu(1-z)} = z \tag{16}$$

These two equations will be solved by using the collected data and the prediction results will be presented in the next section.

3. **Some Experimental Results.** Now we shall implement the prediction model developed in the previous section by using the real life collected data. To be specific, we have collected the number of posture changes of 25 pregnant cows by continuous video monitoring until it takes delivery. In our experiment, we utilize 3 days data prior to the occurrence of actual calving event. Sample data for cow ID 2 are shown in Table 1. By using the sample data from Table 1, we compute the mean m during the first 48 hours. We obtain mean $m = 0.791667$.

Table 1. Sample hourly data for posture changes counts

Time (hr)	Counts	Time	Counts	Time	Counts	Time	Counts
−72	0	−54	2	−36	0	−18	2
−71	0	−53	3	−35	1	−17	2
−70	0	−52	2	−34	0	−16	2
−69	1	−51	1	−33	0	−15	1
−68	1	−50	0	−32	0	−14	3
−67	0	−49	0	−31	0	−13	4
−66	1	−48	0	−30	0	−12	1
−65	1	−47	0	−29	1	−11	1
−64	2	−46	2	−28	2	−10	0
−63	1	−45	0	−27	3	−9	0
−62	1	−44	1	−26	0	−8	1
−61	2	−43	1	−25	0	−7	2
−60	1	−42	1	−24	0	−6	8
−59	1	−41	1	−23	2	−5	2
−58	0	−40	2	−22	0	−4	8
−57	0	−39	1	−21	0	−3	14
−56	0	−38	2	−20	0	−2	15
−55	0	−37	0	−19	0	−1	12

3.1. **Computation procedure geometric sequence.** Using (2) and (12), we have

$$G(z) = \frac{p}{1 - qz} = z \tag{17}$$

However, from (4), we have $p = 1/(1+m)$ and $q = m/(1+m)$. In this case, since $m = 0.791667$, we get $p = 0.55814$ and $q = 0.44186$. Thus, we solve Equation (17) by iteration method as follows. In order to do so, we rewrite equation as shown in (18).

$$z = \frac{G(z) + z}{2} \tag{18}$$

For iteration, we write Equation (18) as

$$z_{n+1} = \frac{G(z_n) + z_n}{2} \tag{19}$$

We then calculate z_n for $n = 0, 1, 2, \ldots, 48$ by assuming $z_0 = 0$. We solve Equation (19), until z_n becomes greater than 1. Then, we take the largest value of z_n which is less than 1 as λ_0. Substituting this value in Equation (13), we finally obtain the predicted calving time.

3.2. **Computational procedure for Poisson distribution.** By using the iteration procedure similar to the geometric case, we obtain the experimental results and the summary of the experimental results for 25 dairy cows as shown in Table 2.

TABLE 2. Some experimental results for geometric and Poisson distribution

Cow ID	λ_0	Predicted calving time using geometric	Predicted calving time using Poisson	Actual calving time (hours)
ID 1	1.6042	71.5915	70.4923	72
ID 2	0.7917	73.5805	71.4030	
ID 3	0.9583	76.3692	73.2906	
ID 4	0.25	70.3199	70.1196	
ID 5	1.2083	74.2196	71.7712	
ID 6	1.0417	76.3836	73.3023	
ID 7	1	76.5535	73.4428	
ID 8	1.1047	75.6717	72.7477	
ID 9	0.6667	71.9558	70.6324	
ID 10	0.9375	76.1457	73.1110	
ID 11	0.7083	72.3934	70.8165	
ID 12	0.8542	74.7231	72.0874	
ID 13	0.7917	73.5805	71.4030	
ID 14	1.0417	76.3836	73.3023	
ID 15	0.9375	76.1457	73.1110	
ID 16	0.9792	76.5074	73.4043	
ID 17	1.0833	75.9479	72.9566	
ID 18	1.3333	72.9321	71.0670	
ID 19	0.8125	73.9435	71.6077	
ID 20	0.3958	70.5833	70.1734	
ID 21	0.4792	70.8306	70.2404	
ID 22	1.25	73.7229	71.4819	
ID 23	1.4792	72.0464	70.6691	
ID 24	0.875	75.1200	72.3531	
ID 25	0.7917	73.5805	71.4030	

3.3. **Discussions.** According to the experimental results shown in Table 2, it has been understood that the two different models give similar results. Also, the two models are easy to implement and only the mean values of a certain periods are necessary to be used as model parameters. On the other hand, it is found that the nature geometric distribution is suitable for it only two events can occur in the calving process namely calving or not calving. So, like the characteristic of geometric distribution, it is to estimate the waiting time to the success or the occurrence of calving event. In Poisson distribution case, it is reasonable to utilize since we are dealing with the number of transitions from one posture to another. Naturally, such data are suitable to Poisson distribution. Thus, we realized that the two proposed models are good enough for calving time prediction. In addition, Table 2 provides both predicted times by using the proposed geometric model and Poisson model and the actual calving times collected from the actual calving data. We found that the majority of the predicted results as accurate as the actual calving times. We also observed that the actual times lie between the results of our two models. Moreover, the proposed models outperform some existing methods such as K-Nearest Neighbors (KNN), Naïve Bayes (NB), and Support Vector Machine (SVM) with respect to accuracy performance.

4. **Conclusions.** In this paper, we had proposed an application of sequential methods to predict time to dairy cow calving event. The method is simple and easy to implement. One of appealing points is that the proposed method needs only a few data prior to calving. The proposed method is only expository nature, and more insight analysis is necessary to have more understanding of calving time prediction. In this paper, we have used only two simple models, it would be worthwhile to look into some complex distributions such as Markov dependent variables. We hope these would be done in our future research.

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