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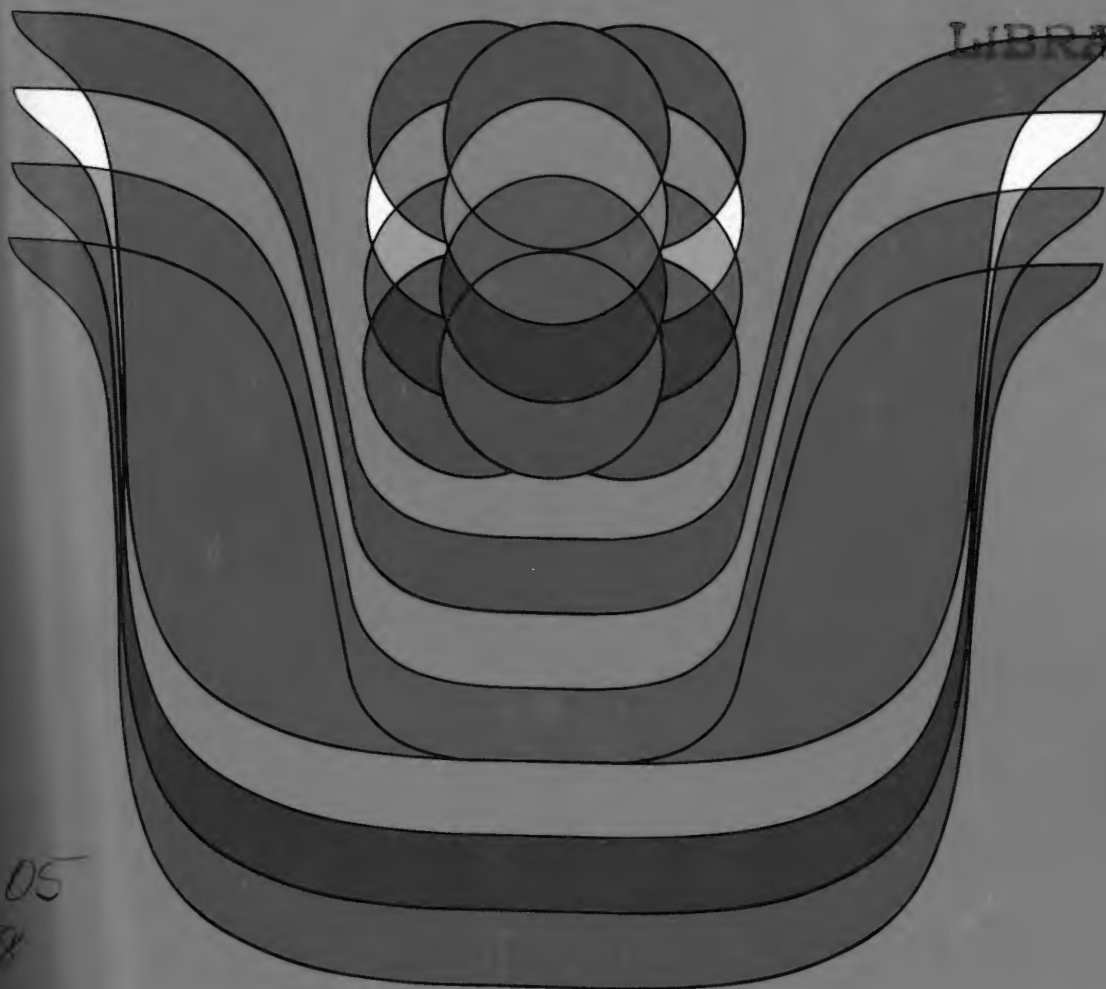
Special Issue: Animal Status Monitoring and
Herd Management, EAAP Publication No. 1/97

LIVESTOCK PRODUCTION SCIENCE

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Official Journal of the European Association for Animal Production (E.A.A.P.)

Revue Officielle de la Fédération Européenne de Zootechnie (F.E.Z.)

Offizielle Zeitschrift der Europäischen Vereinigung für Tierproduktion (E.V.T.)

Официальный Журнал Европейской Ассоциации по Животноводству (ЕАЖ)

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Printed in The Netherlands

Special Issue

Animal Status Monitoring and Herd Management

**Proceedings of the session of Animal Status Monitoring and Herd Management
of the 47th Annual Meeting of EAAP, held in Lillehammer, Norway, 25–29
August 1996**

EAAP Publication No. 1/97

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Results of a multivariate approach to automated oestrus and mastitis detection

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Abstract

In modern dairy farming sensors can be used to measure on-line milk yield, milk temperature, electrical conductivity of quarter milk, concentrate intake and the cow's activity. Together with information from the management information system (MIS), the sensor data can be used for the automated detection of oestrus and diseases. A model has been developed to process the measured variables in a multivariate way. This model is based on time series analysis combined with a Kalman filter. Sensor data, MIS information and reference data of two experimental farms (approx. 90 cows for two years) were available to test the model. The test results were expressed in sensitivity, the percentage of True Positive alerts, and specificity, the percentage of True Negative alerts. For oestrus, it gave in a sensitivity ranging from 94% to 83% (with the level of significance ranging from 95% to 99.9%), coupled with a specificity from 95% to 98%. For clinical mastitis a sensitivity ranging from 96% to 65% was found, for subclinical mastitis it was ranging from 100% to 57%; the coupled specificity for mastitis (clinical and subclinical) was ranging from 95.3% to 99.4%. For other diseases, a sensitivity ranging from 99.6% to 76.8% with a specificity from 86% to 97% was found. Some possibilities to improve these results are discussed. © 1997 Elsevier Science B.V.

Keywords: Dairy cows; Oestrus detection; Mastitis detection; Time series analysis; Kalman filter

1. Introduction

Early detection of oestrus and diseases is important in dairy husbandry. A proper detection of oestrus leads to a higher success rate for inseminations and to preset calving intervals. Diseases should be detected early to minimize the production losses and other adverse consequences, especially mastitis is a frequently occurring disease with negative effects. The losses caused by fertility problems are estimated at Dfl. 80 per cow per year (Dijkhuizen et al., 1985),

and the losses caused by mastitis at US\$ 83 (approx. Dfl. 140) per cow per year (Houben et al., 1994).

Some developments augment the need of improved and automated detection of oestrus and diseases. First, there is a tendency to larger herds in dairy practice. In The Netherlands the percentage of farms with more than 100 cows increased from 0.7% in 1975 to 4.5% in 1995 (Agricultural, 1996). The classical detection method of visual observations is more difficult and time-consuming in larger herds. Second, the introduction of robotic milking makes milking possible in the absence of the farmer. Visual observations of abnormalities of cows during milking are not possible in that case. Therefore, visual

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observations of the farmer in the cowhouse are supported by automated detection in the milking parlour. Furthermore, the importance of mastitis detection will increase in the near future, due to increasing milk quality demands. For example, the requirements as regards the somatic cell counts in the milk will be strengthened.

Automated detection is possible using sensor measurements and information from a Management Information System (MIS) as described in Schlünsen et al., 1987; Hogewerf et al., 1992; De Mol et al., 1993. The sensors measure variables such as milk yield, milk temperature, feed intake, electrical conductivity of the milk and activity of the cow. These variables are more or less aberrant due to oestrus or a disease. Information from the MIS is useful for the judgement of the causes of aberrations. An occurrence of oestrus is more likely when the last known oestrus case was about three weeks ago. Occurrences of a disease may be more likely if previous occurrences of the same disease were recorded.

A model which combines all available data and transforms it into useful information to the farmer is the missing link for automated detection. The output of a detection model should consist of alerts to the farmer (warning him that certain cows are likely to be diseased or in heat). The farmer can then take appropriate action for these cows.

Much research has been done on the development of sensors and appropriate models to detect oestrus and diseases. Milk temperature can be used to detect oestrus (Maatje and Rossing, 1976; McArthur et al., 1992). The activity of cows (usually measured by pedometers) is also used for oestrus detection (Rossing et al., 1983; Lehrer et al., 1992; Koelsch et al., 1994; Scholten et al., 1995). Sensors for mastitis detection are often based on measurements of the electrical conductivity of quarter milk (Rossing et al., 1987; Maatje et al., 1992; Nielen, 1994). The milk yield may be used for the detection of clinical diseases (Distl et al., 1989; Deluyker et al., 1991). Only single variables are considered in the described models or different variables are considered successively. The occurrence of oestrus however, may lead not only to increased cow activity but also to increased milk temperature and decreased milk yield. Mastitis may lead to increased milk conductivity and milk temperature as well as decreased milk yield. A

disease may influence the milk yield, milk temperature, cow activity and feed intake. This suggests that the results of a detection model may be improved by combining the variables.

MIS's have been created for dairy farming and other branches of agriculture (Kroeze, 1990; Kroeze and Oving, 1987). An extension to these management information systems is the addition of decision support systems (DSS), which shifts the emphasis from recording to the use of recorded data in decision support models. A detection model is an example of such a DSS. The use of data from the MIS can improve the performance of the detection model (Hogeveen et al., 1991).

Results from a newly developed model for oestrus and diseases detection in dairy cows are described in this paper. This model is different from previous developed models in the multivariate approach and in the possibility of an integrated use of MIS information.

2. Material and methods

2.1. Sensor data

Sensor data were recorded on two locations for two years: 36 lactating cows on the experimental farm of IMAG-DLO in Duiven from January 1993 till December 1994, and 60 cows on the experimental farm of ID-DLO in Lelystad during the same period (with intermissions during the summer holidays). The cows were housed in a cubicle house with slatted floor. Individual concentrate rations were provided by automated concentrate dispensers. The cows were milked two times a day, the complete data set contained 75 077 milkings.

Individual cows were identified automatically, and the following data were recorded automatically with sensors in the milking parlour (Maatje et al., 1992):

- milk yield
- milk temperature, the maximum temperature during a milking;
- activity, the counter value of an activity tag attached to the right foreleg;
- electrical conductivity of the milk, measured for each quarter seven times per second and averaged over 5 s, the average of the 20 highest values being recorded.

The concentrates rations were determined by the MIS per cow and per day, the leftovers were recorded each morning.

The sensor data were stored in a database, which was part of the MIS of the experimental farms. Sensor data together with additional information from the MIS (the cow status) are input for the detection model. The milk temperature and conductivity are corrected for sensor influences in a similar way as indicated by Hogewerf et al. (1992).

2.2. Reference data

Reference data, consisting of laboratory examinations of milk samples and observations by herdsman and veterinarian, are necessary to be able to evaluate the output of the detection model.

Reference data for oestrus detection are progesterone concentrations in mixed milk samples, visual observations by the herdsman and rectal palpations of the ovary and reproductive tract by the veterinarian. Reference data for mastitis detection are mixed milk somatic cell counts twice weekly, bacteriological examinations of quarter milk samples every two months, quarter milk somatic cell counts every two months and clinical observations. Veterinary inspections were carried out periodically (once or twice a week) and after consultation.

A cow is in oestrus, according to the reference data, if the progesterone level in milk is low (≤ 7 ng/ml) and a low progesterone level is preceded and followed by a high level. Visual observations, recorded in the MIS, are only used if available to confirm the date of oestrus. The date is assessed in the centre of the period of low progesterone, if there is no observation available. A cow is also considered to be in oestrus if the first increase in progesterone level after calving can be coupled with a visual heat observation.

A cow is suffering from clinical mastitis if clinical signs (clots in the milk or swollen quarters) are present; and from subclinical mastitis if, for one or more quarters, the cell count exceeds 500,000/ml and mastitis pathogens are established.

Occurrences of other diseases were indicated by the veterinarian or herdsman. These were divided into five categories: locomotion, digestive upsets, reproduction, udder health and others.

2.3. Model description

The input of the detection model is built up from the sensor data and MIS information (calving date, date of last observed oestrus date, status of cow). The main output consists of alerts for oestrus and diseases, especially mastitis. These alerts indicate cows that need the farmer's attention ('management by exception').

The model is based on time series analysis combined with a Kalman filter approach, as depicted in Fig. 1 (De Mol et al., 1996). Time series models have been derived for milk yield, milk temperature, cow activity and milk conductivity. The parameters of these models appeared to be cow-dependent. A multivariate approach is not possible with time series models for single variables. A Kalman filter is a method to estimate the state of a system on-line. By defining the state as the parameters of the time series

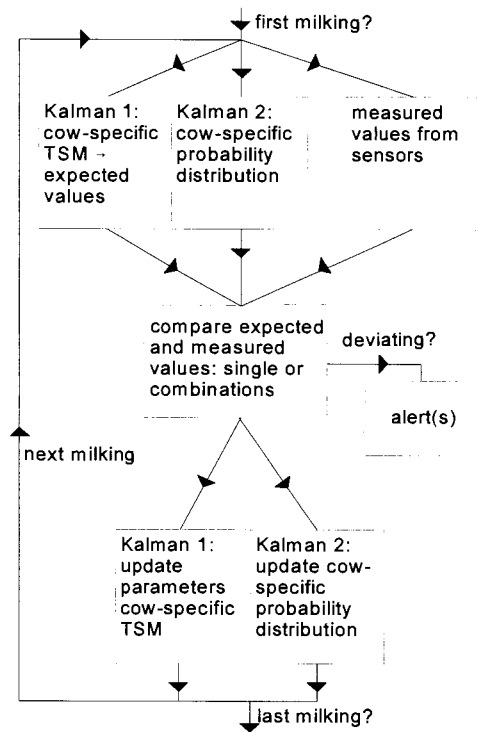


Fig. 1. Flow-chart of the detection model with the interaction between the underlying time series models (TSM) and the probability distribution with the Kalman filters.

models, the application of a Kalman filter makes it possible to estimate for each cow after each milking:

- updated parameter values;
- the multivariate distribution of the parameters (and of the multivariate error).

This approach provides each cow with her own model, which describes the characteristics and variability of that individual cow. An alert is given when the measurements fall outside the normal pattern for the particular cow.

Concentrate intake is not modelled by time series. A probability distribution for the leftover as a percentage of the ration is used. This probability distribution also appeared to be cow-dependent. Therefore, this distribution is fitted for each cow every day with a second Kalman filter, where the probability distribution is regarded as the state, to get cow-specific distributions.

An alert is given when a single variable or a combination of variables is deviant. Such combinations are:

- for oestrus: increased activity, increased milk temperature and decreased milk yield;
- for mastitis: increased conductivity of quarter milk, increased milk temperature and decreased milk yield;
- for other diseases: increased milk temperature, decreased milk yield, decreased activity and increased concentrates leftovers.

Alerts can be given at various levels: they are given for single variables or combinations of variables falling outside a 95%, a 99% or a 99.9% confidence interval. MIS information can additionally be used to establish alerts. In the current version of the model, this is only done for oestrus: an oestrus case is more likely if a previous observed oestrus was about three weeks ago.

2.4. Implementation of the detection model

The detection model has been designed as a black box to be independent of the MIS used and to be able to compare the time series model with other detection models. The black box does not have a memory, all information needed is passed to the black box by an input file (with cow data, sensor data and model-oriented data). The black box delivers an output file with alerts and updated model-ori-

ented data. Any cow, that is new for the model, starts with average model parameters and an average multivariate distribution; these give reasonable results but the results improve as more information of that cow (data of more milkings) becomes available.

The MIS software was originally developed by IMAG-DLO but has been commercialized by Argos/Uniform (Kroeze, 1990). The communication with the black box has been made independent of the MIS by applying the ADIS protocol (Machinery, 1995).

2.5. Test protocol

The alerts of the detection model were evaluated by using the reference data. Test results are available for two data sets: Duiven and Lelystad, where data have been collected in 1993 and 1994. Each case of oestrus, mastitis or disease is classified as True Positive (TP) if one or more alerts are given or as False Negative (FN) if no alerts are given. The TP alerts must fall within a certain period around the date established. The length of the periods is given in Table 1. Periods round a case of disease can overlap, two mastitis cases with an overlap in the periods are taken as two cases, two cases of another illness with an overlap are taken as one case (with a longer period). The sensitivity is the percentage of TP cases:

$$\text{Sensitivity} = \frac{TP}{(TP + FN)} \cdot 100\%$$

A milking outside an oestrus, mastitis or disease period is True Negative (TN) if no alert is given or False Positive (FP) if an alert is given. The specificity is the percentage of TN milkings:

$$\text{specificity} = \frac{TN}{(TN + FP)} \cdot 100\%$$

Table 1

The length of the period around the date established for a case of oestrus, mastitis and other diseases

Type	Length of period
oestrus	from 2 days before till 1 day afterwards
clinical mastitis	from 10 days before till 7 days afterwards
subclinical mastitis	from 14 days before till 14 days afterwards
other diseases	from 7 days before till 7 days afterwards

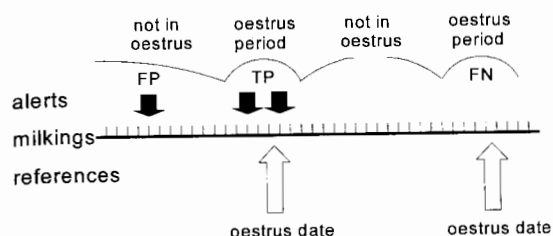


Fig. 2. Illustration of the test protocol for oestrus for a cow with two oestrus dates (one case TP, the other FN) and an FP milking outside the oestrus periods.

This test protocol is illustrated for oestrus in Fig. 2, where two oestrus dates are established. The first case is TP, because alerts are given within the oestrus period, the second case is FN because no alert is given. Alerts outside the oestrus periods are FP, milkings outside these periods without an alert are TN.

Alerts for oestrus can only be generated if activity measurements are available. Sometimes, measurement errors occurred during the test period, these were caused by missing or erroneous pedometers, or by errors in reading the step counter values. A question mark is given for such a milking to note the impossibility of making a judgement. The missing value is replaced with the expected value for successive milkings to prevent a chain reaction of one disturbance leading to a series of question marks. An oestrus period with question marks is still TP when one or more alerts are given, it is not considered FN when there are no alerts.

3. Results

3.1. Detection of oestrus

The evaluation of single (based only on activity) and combined alerts (based on a combination of variables) for oestrus are given in Table 2 (sensitivity) and Table 3 (specificity). The cow status, as known by the MIS, is used to exclude oestrus alerts for cows that are in calf or dry.

The results depend on the chosen confidence interval for the alerts. Tightening the criterion leads to a lower sensitivity and higher specificity, and vice versa. A logistic regression model have been used to test the significance of the differences between single and combined alerts and of the differences between Duiven and Lelystad. The combined alerts give a significantly higher sensitivity and specificity when a 95% confidence interval is used. The sensitivity results for Lelystad are better in some cases, the higher specificity for Duiven is significant in all cases.

The sensitivity of farm observations appeared to be 72% (386 cases were notified). This figure should be handled with care because alert lists of prototypes of the model were available and may have influenced the visual observations. Some further analysis has been done for Duiven. The FP alerts have been examined, most were during summer and probably caused by weather circumstances, other FP alerts may be caused by other cows being in oestrus.

Table 2

Classification of oestrus cases (TP, FN or ?) and sensitivity of single (based only on activity) and combined alerts for different confidence intervals; for the complete data set and both farms separately

Alerts		Total: 537 cases				Duiven: 179 cases				Lelystad: 358 cases			
		TP	FN	?	Sensitiv.	TP	FN	?	Sensitiv.	TP	FN	?	Sensitiv.
Single	95%	435	42	60	91.2% ^a	135	17	27	88.8%	300	25	33	92.3%
	99%	411	64	62	86.5%	123	29	27	80.9% ^b	288	35	35	89.2% ^b
	99.9%	378	89	70	80.9%	111	38	30	74.5% ^b	267	51	40	84.0% ^b
Combined	95%	451	28	58	94.2% ^a	141	12	26	92.2%	310	16	32	95.1%
	99%	411	64	62	86.5%	127	25	27	83.6%	284	39	35	87.9%
	99.9%	387	82	68	82.5%	117	34	28	77.5% ^b	270	48	40	84.9% ^b

^a Significant difference between single and combined alerts at $P < 0.05$.

^b Significant difference between Duiven and Lelystad at $P < 0.05$.

Table 3
Classification of milkings (FP, TN or ?) outside oestrus periods (cows in calf or dry excluded) and specificity of single (based on activity only) and combined alerts for different confidence intervals; for the complete data set and both farms separately

Alerts		Total: 41803 milkings				Duiven: 12935 milkings				Lelystad: 28868 milkings			
		TN	FP	?	Specif.	TN	FP	?	Specif.	TN	FP	?	Specif.
Single	95%	34863	1619	5321	95.6% ^a	10358	417	2160	96.1% ^b	24505	1202	3161	95.3% ^b
	99%	35418	1064	5321	97.1%	10512	263	2160	97.6% ^b	24906	801	3161	96.9% ^b
	99.9%	35755	727	5321	98.0%	10610	165	2160	98.5% ^b	25145	562	3161	97.8% ^b
Combined	95%	34462	2020	5321	94.5% ^a	10243	532	2160	95.1% ^b	24219	1488	3161	94.2% ^b
	99%	35363	1119	5321	96.9%	10505	270	2160	97.5% ^b	24858	849	3161	96.7% ^b
	99.9%	35802	680	5321	98.1%	10620	155	2160	98.6% ^b	25182	525	3161	98.0% ^b

^a Significant difference between single and combined alerts at $P < 0.05$.

^b Significant difference between Duiven and Lelystad at $P < 0.05$.

Table 4
Classification of mastitis cases (TP or FN) and sensitivity of single (based on conductivity only) and combined alerts for different confidence intervals; for the complete data set; for clinical and subclinical mastitis

Alerts		Clinical mastitis: 52 cases			Subclinical mastitis: 21 cases		
		TP	FN	Sensitiv.	TP	FN	Sensitiv.
Single	95%	26	26	50% ^a	16	5	76%
	99%	25	27	48% ^a	10	11	48% ^a
	99.9%	19	33	37% ^a	5	16	24%
Combined	95%	50	2	96% ^a	21	0	100%
	99%	47	5	90% ^a	16	5	76% ^a
	99.9%	34	18	65% ^a	12	9	57%

^a Significant difference between single and combined alerts at $P < 0.05$.

Table 5
Classification of milkings (FP or TN) and specificity of single and combined alerts for cows without mastitis and different confidence intervals; in total and for each farm separately

Alerts		Total: 16 cows, 6495 milkings			Duiven: 5 cows, 2432 milkings			Lelystad: 11 cows, 4063 milkings		
		FP	TN	Specific.	FP	TN	Specific.	FP	TN	Specific.
Single	95%	257	6238	96.0%	61	2371	97.5% ^b	196	3867	95.2% ^b
	99%	78	6417	98.8%	13	2419	99.5% ^b	65	3998	98.4% ^b
	99.9%	37	6458	99.4%	3	2429	99.9% ^b	34	4029	99.2% ^b
Combined	95%	303	6192	95.3%	88	2344	96.4% ^b	215	3848	94.7% ^b
	99%	117	6378	98.2%	24	2408	99.0% ^b	93	3970	97.7% ^b
	99.9%	40	6455	99.4%	8	2424	99.7% ^b	32	4031	99.2% ^b

^b Significant difference between Duiven and Lelystad at $P < 0.05$.

Table 6
Classification of cases of disease (TP or FN) and sensitivity of combined alerts for different confidence intervals; for the complete data set and both farms separately

Alerts		Total: 263 cases			Duiven: 61 cases			Lelystad: 202 cases		
		TP	FN	Sensitiv.	TP	FN	Sensitiv.	TP	FN	Sensitiv.
Combined	95%	262	1	99.6%	61	–	100.0%	201	1	99.5%
	99%	238	25	90.5%	54	7	88.5%	184	18	91.1%
	99.9%	202	61	76.8%	45	16	73.8%	157	45	77.7%

Table 7

Classification of milkings outside disease periods (TN or FP) and specificity of combined alerts for different confidence intervals; for the complete data set and both farms separately

Alerts		Total: 40286 milkings			Duiven: 12526 milkings			Lelystad: 27760 milkings		
		TN	FP	Specific.	TN	FP	Specific.	TN	FP	Specific.
Combined	95%	34630	5656	86.0%	10628	1898	84.8% ^a	24002	3758	86.5% ^a
	99%	37674	2612	93.5%	11666	860	93.1% ^a	26008	1752	93.7% ^a
	99.9%	38940	1346	96.7%	12104	422	96.6%	26836	924	96.7%

^a significant difference between Duiven and Lelystad at $P < 0.05$.

3.2. Detection of mastitis

The sensitivity for mastitis detection has been calculated for clinical and subclinical mastitis. The results are given in Table 4. The sensitivity of combined alerts is significantly higher for clinical mastitis, for subclinical mastitis only in case of the 99% confidence interval.

The specificity for mastitis is more difficult to determine since the mastitis status is not known in periods between two sampling dates. Quarter milk samples were collected every two months, a mastitis alert halfway through this interval may be FP as well as TP. Therefore, the specificity for mastitis is determined in another way. Cows were selected, for which mastitis pathogens were never established and for which the cell count of the quarter milk or the mixed milk never exceeded 500,000/ml. Alerts for these cows without mastitis were classified as FP and used to calculate the specificity. The results are given in Table 5. This has been done for both single and combined alerts, the differences are not significant. The specificity for Duiven is significantly higher than for Lelystad in all cases.

3.3. Detection of other diseases

Single alerts for other diseases are difficult to define since it is difficult to couple a single variable to a every kind of disease. Only combined alerts are used for other diseases. The results are presented in Table 6 (sensitivity) and Table 7 (specificity).

The differences in sensitivity between Duiven and Lelystad are not significant; the specificity for Lelystad is significantly higher than for Duiven in case of a 95% or 99% confidence interval.

The sensitivity and specificity for diseases depends strongly on the chosen confidence interval. A very high sensitivity is coupled with a low specificity. The detection results were mostly in proportion to the known influence of diseases to the measured variables. For example, fever was detected well and results for acetonaemia were worse.

4. Discussion

The detection model has been tested as regards the data from two experimental farms in Duiven and Lelystad. The data from Duiven became available during the model development period. These data have partly been used to determine the model structure; the data of Duiven have also been used for testing. The data from Lelystad have only been used for testing. The results are farm-dependent, but there is no structural difference, the results of Lelystad are sometimes better and sometimes worse than the results of Duiven. This may indicate that the model is generally applicable but further testing is needed to prove this fact. A general applicability may be expected since the model structure gives each cow an individual model, which is updated after each milking.

The data collection period is very long for such research. As much as possible the recorded data are used. No cows or periods are excluded from testing. Measurement errors are taken into account. Their occurrence may also be expected in practical farming situations. These features make it difficult to compare our results with other research results; overviews can be found in Lehrer et al., 1992 for oestrus and in Nielen et al., 1992 for mastitis. In practice, the

sensitivity and specificity will depend on the farmer's attitude but they may reach the same level as in the present research. Testing on other farms, however, is recommended.

The definition of the periods as mentioned in Table 1 is not a matter of course. These were chosen with the available reference data taken into account. In a follow-up research other definitions and the timeliness of alerts will be examined.

The sensitivity and specificity are mutually dependent. Increasing the sensitivity by choosing another alert level leads to a decreased specificity, and vice versa. A high sensitivity is preferred when no cases should be missed and when false positive alerts are no problem. A high specificity is better when false positive alerts should be avoided. An optimum level may be determined by minimizing the sum of the costs of FP alerts and FN alerts.

The results for oestrus detection are influenced by measurement errors, which is indicated by the number of cases and milkings with question marks in Tables 2 and 3. The increase in activity due to oestrus is temporary and can easily be missed if the sensors should fail in the oestrus period. This stresses the need of adequate data management and reliable sensors. The influence of measurement errors is less important in case of mastitis and diseases. This is because the periods considered for these cases are longer (Table 1).

The sensitivity is fairly high for oestrus detection. It may be difficult to improve these results by applying sensor measurements only. Some cases will never be detected, because the variables hardly change during oestrus (e.g. in case of a silent heat). The specificity may be improved. This could be done by applying more of the MIS information (it is hardly used in the current model) and by taking group influences into account for the generation of alerts (this is not yet included in the model).

The results for mastitis with single alerts are much worse than with combined alerts, which shows the relevance of a multivariate approach. The sensitivity for mastitis is rather high for combined alerts with a low or medium level. A high alert level leads to a sharp decrease in sensitivity. The underlying alert rules may be improved. The specificity seems reasonable but the number of FP alerts may still be too high for practical application. Further research to

sensor improvements may be worthwhile. The sensitivity may also be improved by taking group influences into account, regarding the number of previous alerts for the same cow and previous occurrences of mastitis.

A multivariate approach seems the best one for the detection of diseases. The sensitivity can be high, but the specificity is (too) low. The detection of other diseases was not one of the main goals of this research. The results may be improved by changing the alert rules and taking other factors, like occurrences of oestrus or previous diseases, into account.

5. Conclusion

The detection model gives promising results. Automated detection of oestrus gives a higher sensitivity than the classical method of observation by the herdsman. The specificity for oestrus detection is encouraging, but may be improved by model adaptations. For oestrus detection a combination of variables gives a slightly higher sensitivity than a single variable approach, with the same specificity.

The results for mastitis are quite good but may not be good enough for practical implementation. Further research seems worthwhile to improve the results, especially the specificity. The results with combined alerts are much better than the results with single alerts. A multivariate approach proves to be very useful for mastitis detection.

The detection results for other diseases are promising. They show that a multivariate approach is valuable for the detection of diseases.

Acknowledgements

This research has been supported by Alfa Laval Agri, Tumba, Sweden.

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