Online warning systems for individual fattening pigs based on their feeding pattern

Jarissa Maselyne[a,b], Annelies Van Nuffel[a], Petra Briene[a,b], Jürgen Vangeyte[a], Bart De Ketelaere[b], Sam Millet[c], Janne Van den Hof[d], Dominiek Maes[d], Wouter Saeys[b,]*

[a]*ILVO (Institute for Agricultural and Fisheries Research), Technology and Food Science Unit, Agricultural Engineering research area, Burg. van Gansberghelaan 115 bus 1, 9820 Merelbeke, Belgium*

[b]*KU Leuven, Department of Biosystems, MeBioS, Kasteelpark Arenberg 30, 3001 Leuven, Belgium*

[c]*ILVO, Animal Sciences Unit, Scheldeweg 68, 9090 Melle, Belgium*

[d]*Ghent University, Department of Obstetrics, Reproduction and Herd Health, Porcine Health Management, Salisburylaan 133, 9820 Merelbeke, Belgium*

**Corresponding author: wouter.saeys@biw.kuleuven.be*

E-mail addresses: jarissa.maselyne@ilvo.vlaanderen.be (J. Maselyne), annelies.vannuffel@ilvo.vlaanderen.be (A. Van Nuffel), petra.briene@gmail.com (P. Briene), jurgen.vangeyte@ilvo.vlaanderen.be (J. Vangeyte), bart.deketelaere@kuleuven.be (B. De Ketelaere), sam.millet@ilvo.vlaanderen.be (S. Millet), jannevandenhof@hotmail.com (J. Van den Hof), dominiek.maes@ugent.be (D. Maes), wouter.saeys@kuleuven.be (W. Saeys)

Abstract

For sustainable pork production and maximum pig welfare, all health, welfare and productivity problems in the barn should be detected as early as possible. In this paper, an automated monitoring and warning system is proposed. Based on measurements of the feeding pattern, it is able to generate daily alerts for individual fattening pigs. Using historical data, the following types of warning systems were developed: (1) fixed limits that treat all pigs and all days equally; and (2) time-varying individual limits using the concept of Synergistic Control. These types of limits were constructed either for the number of registrations per pig or the average interval between feeding visits of a pig, leading to four warning systems in total. These warning systems were used to generate alerts during an online validation period. During an entire fattening period, all pigs were individually monitored to establish true alerts, false alerts and missed problems. The best performance was achieved for the Synergistic Control method on the number of registrations, with a sensitivity of 58.0 %, specificity of 98.7 %, accuracy of 96.7 % and precision of 71.1 %. Severe problems were detected on average within 1.3 days from the start of the problem. These are promising results that provide a solid basis for the development of a system for individual pigs but further improvements are warranted to make the system more practical.

Keywords: pigs, feeding pattern, warning system, RFID, Synergistic Control, decision support

Nomenclature

# reg	number of registrations
ADG	average daily gain
ARL_0	in-control average run length
ARL_1	out-of-control average run length
avIVI	average inter-visit interval
EPC	engineering process control
FN	false negative
FP	false positive

LCL lower control limit

n number of pig-days

NaN not a number

RFID radio frequency identification

SGC synergistic control

SPC statistical process control

TN true negative

TP true positive

UCL upper control limit

1 Introduction

In pig farming, disease control, animal welfare and production efficiency are important factors to help ensure sustainable pork production and maintain an economically viable farm. Therefore, it is important that health, welfare and productivity problems in the barn are detected and treated early. As the sector intensifies and farms and groups of pigs become larger, visual monitoring of the pigs as a sole tool for problem detection could be suboptimal. Visual monitoring gives only a snapshot-view on the animals appearance (Heitkämper et al., 2011; van der Heuvel et al. 2004) and is often more focused on the group level than the individual level in pig farming. Automated monitoring or Precision Livestock Farming (PLF) (see for example Wathes et al. (2008) and Banhazi et al. (2012)) allows to monitor the livestock online and continuously (Matthews et al, 2016). The automatically gathered measurement data can be transformed into information for the farmer and support the farmer's decision making-process

(Cornou and Kristensen, 2013). Using the right techniques, automated monitoring can also be done at the individual pig level, allowing for individual, custom-made care.

Disease, welfare and productivity problems can have an impact on the feeding pattern of a pig (Brown-Brandl et al., 2013; Hart, 1988; Hessel and Van den Weghe, 2011), such as a reduced feeding time or longer intervals between visits . Therefore, a system to measure individual pigs' feeding patterns has recently been developed and validated (Maselyne et al., 2014a; Maselyne et al., 2014b). Using high frequency (HF) Radio Frequency Identification (RFID), each pig's attendance at the feeder is registered (Maselyne et al., 2014a). From these raw data, feeding pattern variables such as the number and duration of feeding visits and pauses between feeding visits of a single pig throughout the day can be calculated (feed intake was not measured) (Maselyne et al., 2016). The present study investigated whether abnormal changes in the feeding pattern of a pig can be detected automatically and used as an (early) indicator for health, welfare and productivity problems.

To detect abnormal changes in the feeding pattern of a pig, fixed limits (the same limit for all pigs and days) can be constructed. However, it has been shown that using a Synergistic Control (SGC) procedure can be a better, alternative option for monitoring livestock production systems (Mertens et al., 2011). SGC combines the power of Engineering Process Control (EPC) and Statistical Process Control (SPC) (Montgomery, 2009). In SPC, control limits allow to differentiate abnormal variation from normal variation (due to age, seasonal effects, etc.). The EPC step pre-treats the raw livestock production data to meet the assumptions of the statistical control chart in the SPC step. Thanks to this combination, the online SGC procedure allows to use pig-specific control-limits, which can be updated with every new measurement. Any abnormal variation detected can then be signalled to the farmer as an alert for a specific pig. Promising results have already been obtained with this SGC approach for monitoring process parameters of flocks of laying hens (Mertens et al., 2008; Mertens et al., 2009) and milk yield of individual dairy cows for mastitis detection (Huybrechts et al., 2014).

Therefore, the aims of the present study were (1) to develop several warning systems with fixed limits or variable, individual limits on promising variables of the feeding pattern, based on historical data; (2) to validate and compare these warning systems online by comparing the alerts with detailed observations.

2 Materials and methods

2.1 Animals and housing

The pigs were housed in an automatically ventilated barn at the experimental farm of ILVO (Melle, Belgium). They were housed in four identical pens. Each pen measured 4.3 m by 9 m with approximately 40 % slatted concrete floor and 60 % solid concrete lying area. In addition to natural light, artificial lighting was provided from 7:00 to 21:00. Water was supplied *ad libitum* via nipple drinkers. Dry pelleted feed was automatically supplied using Swing MIDI feeders (Big Dutchman Pig Equipment GmbH, Vechta, Germany). The pigs were fed a commercial feed with 9.3 MJ net energy, 15.50 % crude protein and 0.92 % lysine *ad libitum*.

The experiments included two batches of fattening pigs; one was used as a '**historical dataset**' to develop the warning systems and then these warning systems were validated online in a '**validation period**'. Experiments were in accordance with EU Directive 2010/63/EU for animal experiments.

2.1.1 Historical data

The warning systems were developed using the data of a fattening period with 152 pigs from January to May 2014. Pen 1 and 4 were filled with 19 barrows and 19 gilts each of about 10 weeks old (Hybrid sow x Piétrain boar; weight equally distributed), and 18 days later also pen

2 and 3 were filled with the same amount of pigs. Starting weight was 24.8 ± 3.9 kg (mean ± standard deviation) and the measurements ended at 108.2 ± 12.0 kg, with an average daily gain (ADG) of 0.72 ± 0.09 kg. Four nipple drinkers and two feeders were present per pen. Animal/feeding place ratio was 4.75/1 for young pigs (four pigs could eat from one feeder) and 9.5/1 for older pigs (two pigs could eat from one feeder), based on observations. Other observations included a daily check by the animal caretakers, weekly weight measurements for the pigs of one pen and three-weekly weight measurements for all pigs in the barn.

2.1.2 Online validation period

The warning systems were then validated online during a fattening period with 140 pigs between January and May 2015. The four pens were filled at the same day with 15 or 16 barrows and 20 or 19 gilts each of about 10 weeks old (Hybrid sow x Piétrain boar), weighing 24.3 ± 3.6 kg. Measurements ended at 111.9 ± 12.7 kg, and the pigs grew 0.70 ± 0.09 kg per day. In the validation period, two nipple drinkers and one feeder were present per pen (animal/feeding place ratio 8.75 to 17.5/1). Using combinations of coloured ear tags, each pig could be identified visually. Observations were more detailed and are described in section 2.5.

2.2 RFID system

A detailed description of the RFID system can be found in previous work (Maselyne et al., 2014a; Maselyne et al., 2014b). The HF RFID system consisted of tags (placed on the pigs' ears – in this case one tag per ear was used), antennas (placed on the feeders), multiplexers and readers connected to a computer. Attendance at the feeder was registered for individual pigs. These registrations are not continuous during feeding, but instead happen every 3 ± 3 s on average (with two tags per pig) (Maselyne et al., 2016). This was inherent to the system (Maselyne et al., 2014b). A lower height of the antenna allows better registrations of small pigs, but when the pigs grow larger, it is more comfortable for them to eat when the antenna is placed higher. Therefore, the antenna height was usually changed once per fattening period. In the fattening period producing the historical data, the height of the RFID antennas was increased from 46 to 50 cm when the pigs were 78 days in pen 2 and 3; in the other pens the height was always 46 cm. In the online validation period, height of the RFID antennas was increased from 46 to 50 cm at day 92 for two pens and day 94 for the other pens.

2.3 Feeding pattern

From the RFID registrations, feeding visits were constructed. This was done using a bout criterion, which is the maximum time gap between registrations of a pig at a feeder to consider these registrations as part of one feeding visit. A bout criterion of 10 s, when using two tags per pig, was found to be optimal for reconstruction of the real feeding pattern from previous analysis (Maselyne et al., 2016). More information on visit construction can be found in Maselyne et al. (2016). From the RFID-based feeding visits, several variables of the feeding pattern can be calculated, such as the number of visits, duration of visits and average gap between visits throughout the day. For development of the warning systems in this study, number of RFID registrations per pig (# reg, which is correlated with observed feeding duration (Maselyne et al., 2014a; Maselyne et al., 2016)) and average interval between RFID-based feeding visits (avIVI) were used. These variables were considered promising for problem detection, as pigs could be expected to eat for shorter durations throughout the day and have longer pauses in-between visits when they are diseased or stressed (Brown-Brandl et al., 2013; Hessel and Van den Weghe, 2011). The # reg also has the advantage of being raw data, without the processing step needed to construct visits (Maselyne et al., 2016). The avIVI has the advantage that it shows little normal variation compared to the other possible variables.

2.4 Warning system construction

In total, four warning systems were constructed based on the historical dataset. The two variables used are # reg and avIVI per day, for each individual pig. For each of these variables a fixed limit (the same threshold for every day and every pig) was determined. Also, daily time-varying individual limits were constructed using the concept of SGC.

The results were then compared with the problems and treatments of the pigs as noted by the caretakers and with the recorded weights of the pigs in the historical dataset. No daily follow-up of the problems was available and the exact timing of the problems was not known accurately, as there were mostly only records of treatments. Therefore, a problem that lasted several days was taken as one problem and the analysis was based on the number of problems and not on the number of days with problems. Alerts were considered true when during or directly preceding detected problems, treatments or deaths, or when average daily growth was below 0.40 kg per day between two weight measurements. Problems were considered detected when at least one alert occurred that was during or directly preceding this problem. Weight problems were not considered in the list of missed problems. Performance (at problem-level, not day-level) was calculated as:

$$Problem\ detection\ rate = \frac{\#\ detected\ problems}{\#\ detected\ problems + \#\ missed\ problems}$$

$$Precision = \frac{\#\ true\ alerts}{\#\ true\ alerts + \#\ false\ alerts} \qquad (1)$$

$$Estimated\ sensitivity = \frac{\#\ true\ alerts}{\#\ true\ alerts + \#\ missed\ problems}$$

Specificity and accuracy were not calculated as the exact timing and duration of the problems were not known. All analyses were performed using MATLAB R2010b (The MathWorks, Inc., Natick, Massachusetts, USA).

2.4.1 Fixed limits

The fixed limits were chosen between the 0.5th and 1st percentiles in the data for # reg (should be above a certain threshold to be normal); and 99.5th and 99.9th percentiles in the data for avIVI (should be below a certain threshold to be normal). Other percentiles did not give good results. Some values between the percentiles were examined with the performance criteria in equation (1). The fixed limit with the best performance was then selected.

2.4.2 Synergistic Control (SGC)

The SGC procedure consisted of a (series of) model(s) in the EPC step and a control chart in the SPC step (De Ketelaere et al., 2011; Mertens et al., 2011). First, the statistical characteristics of the RFID based feeding variables were analysed. Stationarity was analysed using a plot of the time series and an Augmented Dickey-Fuller test (adftest, MATLAB R2010b). Normality was checked based on a histogram, a normal probability plot and a Lilliefors test on the individual pigs' data (lillietest, MATLAB R2010b). Autocorrelation in the data was analysed using a scatter plot of (y_t, y_{t+1}) and the autocorrelation function. Based on this analysis, a (series of) model(s) is used in the EPC step to pre-treat the raw data to meet the assumptions (stationarity, independence and normally distributed) related to the SPC step. The used models were chosen based on the characteristics and patterns in the feeding variables. To achieve stationarity, typically a trend model is used with parameter values adapted to the subject (in this case the individual pig). Then, an ARMA model can be used to correct for autocorrelation present in the data. Finally, if the data are not normally distributed, the choice of the control chart in the SPC step must be adapted to this (Montgomery, 2009).

A Shewhart control chart for individual measurements (especially designed for the detection of large process shifts) was then applied to the residuals (raw data minus EPC model estimates) in the SPC step. A Shewhart control chart was chosen to establish the potential of SGC on individual pig measurement data, because serious health and welfare problems are expected to result in large process shifts. The data were visualized on a control chart and control limits were determined. With *x* the residuals, the control limits are typically equal to

$$control\ limits = \bar{x} \pm 3\ \frac{\overline{MR}}{d_2} \qquad (2)$$

With $\overline{MR}$ *the average of the moving ranges of two observations* $MR_i = |x_i - x_{i-1}|$*;*

d_2 *a parameter dependent on the sampling size, for sampling size equal to one this is* $d_2 = 1.128$ *(Chapter 6 and Appendix Table VI in Montgomery, 2009).*

However, deviations from these standard control limits are possible. Control limits can be one- or two-sided and extra sensitizing rules can be added (extra rules designed to generate or discard alerts) (Montgomery, 2009). Points outside the control limits are considered out-of-control, whilst all other points are in-control.

For an online, recursive procedure, the model and control limits were initialised for every individual pig during a five-day reference period (initial values were recursively estimated based on in-control data-points alone). If using only this procedure, no alerts would be generated during this reference period. After the reference period, for every new measurement point (so for every day) the residuals were compared with the control limits. If the data-point was considered in-control, it was then used to update the model and control limits for the next measurement point. For the model estimation, it was investigated whether all previous data-points should be considered or only the most recent measurement points (use of a time window in which only the most recent points are considered to estimate the model or use of a forgetting factor (weighing of the data-points with larger weights for more recent points)). Days with technical problems that hindered the RFID measurements for several hours were considered as ‘missing data’ and received the value NaN (not a number). Also the out-of-control points were set at NaN for calculation of the models and control limits to avoid that the model would accept this out-of-control data as normal behaviour.

The final choices made for the design of the model and control chart were based on the results of the performance criteria in equation (1) for the resulting chart for the historical dataset.

2.5 Observations validation period

During the online validation period, normal routine observations were performed daily by the animal caretakers. Observed problems and performed treatments were noted in a logbook.

On every week-day, two observers performed a detailed check-up of the individual pigs. One observer entered the pens to observe the pigs closely and to encourage every lying pig to stand up and walk. The other person observed from outside the pen and made notes. All abnormalities were noted and attention was given to all aspects of the pigs’ appearance and behaviour. If fever was suspected, rectal temperature was measured. Historical observation data of the pigs were available to follow-up on previously noted problems.

The alerts for the four warning systems, as developed based on the historical dataset, were generated daily on week-days using the data of the previous day. The alerts for Friday, Saturday and Sunday were generated separately on Monday. After the check-up by the observers, every pig that had an alert for a warning system was observed closely, using a check-list containing activity, position of the ears, soiling of the skin, body shape and condition, nerve symptoms, respiration, lameness, swellings, skin, eyes, ears, snout, perineum and limbs. Rectal temperature was measured and each of these pigs was also scored for skin, ear and tail lesions, soiling, body condition, bursitis and lameness. The scoring systems used were in accordance with the Welfare Quality Protocol (Welfare Quality®, 2009) or elaborated (in the case of ear and tail biting) according to the experience of trained observers and according to Telkänranta et al. (2014).

On a two-weekly basis, all pigs were weighed and their rectal temperature was measured. At this occasion, abnormalities were also noted and each pig was scored for skin, ear and tail lesions, soiling, body condition, bursitis and lameness.

Every two weeks, a veterinarian performed a thorough clinical check-up of each of the pens (with the observers present), looking for any irregularities in the pigs (general condition, respiration, diarrhoea, locomotion, skin, body condition and barn conditions). If necessary, treatments were performed or suggested for the animal caretakers to perform.

Pigs that were found dead or had to be euthanized were sent to a diagnostic laboratory (Animal Health Care Flanders) for necropsy, and possible follow-up diagnostic work to establish a conclusive diagnosis. A detailed report was sent back to the observers.

At the slaughterhouse, all carcasses were identified individually to link each pig to its carcass data. The lungs were individually examined and scored for presence of pneumonia, fissures and pleurisy according to the scoring method used by Michiels et al. (2015). The total area of lung tissue affected by pneumonia lesions representing the severity of these lesions was calculated (Morrison et al., 1985). The liver was scored for the presence or absence of white spots and also the presence of abscesses in the lungs was noted.

2.6 Performance evaluation

During the validation period, the four warning systems were used online (every day new alerts were generated). By comparing these alerts to the extensive observations performed on a daily basis, performance of the warning systems was determined. The performance was based on the following values:

$$Sensitivity = \frac{TP}{P} \qquad (3)$$

$$Specificity = \frac{TN}{N}$$

$$Accuracy = \frac{TP + TN}{P + N}$$

$$Precision = \frac{TP}{TP + FP}$$

With TP = number of true positives = number of true alerts;

FP = number of false positives = number of false alerts;

TN = number of true negatives = number of pig-days when no alert occurred and no problem was present;

FN = number of false negatives = number of pig-days when no alert occurred, but a problem was present and should have been detected (missed problems);

P = TP + FN = number of positives = number of pig-days with problems necessary to detect;

N = TN + FP = number of negatives = number of pig-days where no problem was present.

As reference data, every pig's status was categorized each day as 'green', 'orange' or 'red', as illustrated in Table 1. A pig with status green did not have any health, welfare or productivity problems and should thus not give an alert. If an alert was generated for this pig, it was considered a **false alert or false positive** (FP). A pig with status orange had mild problems, which results in a **true alert or true positive** (TP) when an alert was present. It was, however, not considered necessary to detect these problems. So, if no alert was present, this was considered a **true negative** (TN) as well. A pig with status red on the other hand should be detected by the system. So, an alert on that day was true and if no alert was present, the problem was missed (**false negative** (FN)). The status was based on the observations and extrapolated when no data were available for that pig on that specific day (for example during weekends).

A list of criteria was established at the beginning of the fattening period to determine the status of the pigs as objectively as possible, as indicated in Table 1. This list of criteria was only a base-line, as many types of problems exist and they can be very variable and occur simultaneously. Status orange was used for a series of problems that do not always require treatment and that, depending on the underlying cause and the individual pig, can vary widely in the effect they can have on the pig's general condition (activity, vitality, pain, welfare). It is likely that these problems will not always relate to a change in the feeding pattern and both spontaneous healing and an aggravating condition can evolve from these conditions. However, for early detection of problems and welfare issues, it is very important to include these problems.

As part of these criteria, an ADG lower than 0.40 kg (which is below 60% of the total ADG of the periods) between two weight measurements equalled one day with red status (so one alert necessary) during that period. An ADG < 0.25 kg / day (which is below 40% of the total ADG of the periods) was set equal to two days with red status between the two weight measurements (requiring two alerts). In addition, as a low growth is not likely to be due to a problem on a single day, all days during the two weeks preceding a weight measurement where an ADG < 0.40 kg was noted were considered status orange. As the daily growth was overall lower in the first two weeks of the fattening period, only pigs with ADG < 0.25 kg / day were considered in those weeks.

A pig with fever was considered status red when its rectal temperature was > 40 °C (Hulsen and Scheepens, 2005). However, during the first three weeks it was noticed that normal body temperatures were very high as the pigs were still young. Therefore, in the first three weeks of the fattening period a temperature between 40 °C and 40.5 °C received status orange, while status red was ≥ 40.5 °C. Pigs could also have elevated body temperatures during weighing due to stress. Pigs with elevated temperatures during weighing were either measured again later on in the pens or the rectal temperature measured in the weighing scale was only considered red if it was ≥ 40.3 °C, as this would be too high to be caused by stress alone.

Performance of the four warning systems was calculated using the formulae in (3). It was also split up for days with orange status and days with red status. The performance of a control chart is often also expressed in terms of the **average run length** (ARL) of the control chart (Montgomery, 2009). Two types of average run length can be calculated. The **in-control ARL** (ARL_0) indicates the average time between false alerts and should thus be as long as possible (Mertens et al., 2011). The ARL_0 was calculated for the best performing warning system as the average time (across the pigs) until the first false alert. Dead and removed pigs were not considered (because these have a shorter measurement period), and the time till the first alert was taken as the number of full measurement days before a false alert was generated for a pig. The **out-of-control ARL** (ARL_1) or average time to signal is the average ARL until an alert is given after a shift of the process. This represents the speed of detection and should be as short as possible (Mertens et al., 2011). The ARL_1 was calculated as the speed of detection for all 'red blocks' (uninterrupted blocks of days with a red status). The same was done for the 'red blocks' that last more than one day. Finally, the FP and FN were analysed for the best performing control chart and some specific cases were analysed in more detail.

3 Results

3.1 Warning systems based on historical dataset

3.1.1 Overview of the historical dataset

In the historical dataset, days with technical problems related to the RFID measurements or the feed and water supply were not considered in the further data analysis. These were four days for the entire barn and an extra 2, 2, 4 and 19 days for the separate pens. Also pigs which had lost an ear tag were removed (four pigs in total).

Data of pigs that were found dead, euthanized or removed were used until the day of removal. Seven pigs of the first batch died and one pig was euthanized. The entire barn had to be treated for coughing in the beginning of the fattening period. Individual treatments were for coughing (one instance), lameness (29 instances and 11 repetitions), stiffness in the limbs (1), severe skin lesion (1) and general illness (3 and 3 repetitions). Thirty problems (which could last multiple days) were determined as necessary to detect. The other 13 problems were considered 'nice to detect', but not considered necessary to detect, as these occurred during technical problems. Weight problems were also considered 'nice to detect'. For the pigs that were weighed weekly (one pen), all pigs grew less than 0.40 kg / day in the first week. Afterwards, another 20 pigs (in total 30 weeks) grew less than 0.40 kg / day. In the other pens, where the pigs were weighed every three weeks, 48 times (for 43 pigs) the daily growth was < 0.40 kg / day, of which 39 times were during the first three weeks.

In Figure 1, the two RFID based feeding variables are illustrated for four healthy pigs in the historical dataset. No problems were noticed by the caretakers for these pigs. So, in theory no abnormal points should be detected. The bottom plots in Figure 1 (pig 136 and 150) correspond to pigs held in the pens where the height of the RFID antennas was increased from 46 to 50 cm at day 96 after the start of the entire fattening period (indicated with a black vertical line). As can be seen, especially in the # reg measured for pig 150, this change in the height of the RFID antennas had an influence on the registered feeding pattern, as the # reg dropped after changing the antenna height. This drop in # reg varied between pigs. After visual inspection of the # reg, an effect of changing the antenna height was found for about 38 % of the pigs in those pens.

Each pig has its individual feeding pattern and inter- and intra-individual variation is clearly present in the plots in Figure 1. A common feature is the sudden decrease of the # reg after the first days in the pen and a recovery afterwards, but this recovery has different magnitudes, delays, durations and time-trends for the different pigs. The avIVI tends to increase for some pigs towards the end of the period in Figure 1, but again the data look very different for the different pigs.

3.1.2 Fixed limits

For the **fixed limit # reg** the 0.5th percentile was 222 registrations and the 1st percentile was 361 registrations per day. The fixed limit was set at 350 registrations (sum of both tags). For the historical dataset, this resulted in 145 alerts of which 58.6 % were true alerts, corresponding to a problem detection rate of 56.4 % and an estimated sensitivity of 83.3 %.

For the **fixed limit avIVI** the 99.5th percentile was 1.18 hr and the 99.9th percentile was 3.45 hr. The fixed limit was set at 1.2 hr. This resulted in 75 alerts of which 49.3 % were true alerts, corresponding to a problem detection rate of 56.3 % and an estimated sensitivity of 72.6 %.

The fixed limits are summarized in Table 2 and shown as black horizontal lines in Figure 1.

3.1.3 Synergistic Control (SGC)

After analysis of the statistical characteristics of the measured data in the historical dataset, normality was found to be sufficient and the data-series were found to be non-stationary. The non-stationarity in the feeding pattern variables of the pigs can be clearly observed in Figure 1. However, this non-stationarity varied between pigs. Therefore, a recursive linear regression model was used to model the non-stationarity in the feeding pattern variables for each pig separately, hereafter called the trend model. The residuals, calculated as raw data minus model estimate, were found to be stationary. Autocorrelation in the residuals was present for some pigs, but not consistent throughout the pigs. Therefore, no model was used to correct for the autocorrelation present in the data (the EPC step of the SGC procedure thus includes only a trend model). A Shewhart control chart was applied directly to the residuals of the linear regression model.

For the **SGC # reg** a one-sided lower control limit was used (except during the reference period, where a two-sided control limit was used to obtain in-control points). Using the standard control limit $LCL = \bar{x} - 3\,\frac{\overline{MR}}{d_2} = -2.66\,\overline{MR}$ (see equation (2)), with premise $\bar{x} = 0$ for the residuals, the number of alerts for the historical dataset was too high (2747 alerts) and increased towards the end of the period. Therefore, wider limits were tested, as well as using only the most recent data for the model ('sliding window' of a certain length) and several sensitizing rules. A good performance was found for the control limit $LCL = -4\,\overline{MR}$. For the estimation of the linear regression model per pig only the last 30 in-control measurement points were used, without forgetting factor. So, a 'sliding window' of length 30 days was used for the model and the measurement points were all weighted equally. Also, measurement points were always considered in-control when the # reg was equal to or larger than 2000, and out-of-control when there were less than 350 registrations of that pig on that day (so an extra fixed limit). These settings led to 234 alerts of which 41.5 % were true alerts, corresponding to a problem detection rate of 68.3 % and an estimated sensitivity of 88.2 %.

The optimal Shewhart control chart for the **SGC avIVI** was with a one-sided upper control limit (except during the reference period, where a two-sided limit was used). Also here, wider limits, a sliding window and sensitizing rules were necessary to reduce the number of alerts to an acceptable level compared to the number of problems that were seen in the barn. The control limit used was: $UCL = 6\,\overline{MR}$. The linear regression model per pig was again based on the last 30 observations (sliding window of length 30). Measurement points were always considered in-control when the avIVI was lower than 0.25 hr. These settings led to 245 alerts, of which 26.4 % were true alerts. Also, 70.3 % of the problems were detected and an estimated sensitivity of 85.5 % was reached.

The details for the SGC methods are summarized in Table 2 together with those for the fixed limits.

3.2 Online validation of the warning systems

3.2.1 Overview of the validation period

In total, there were 124 complete measurement days on 140 pigs. Days with technical problems related to the RFID measurements were excluded from the analysis: seven days for the entire barn plus two days for one pen. These technical problems were a transmission error in the RFID measurement software which stopped the measurements automatically (three times) or a crash of the measurement computer (once). The problem which lasted two days in one pen was due to a loose contact in the RFID antenna cable after increasing the height of that antenna. These problems required an observer to spot the problem and restart the measurements manually.

Also, data of pigs that were found dead, euthanized or removed were only used up until the day of removal. Twenty-one pigs did not make it until the end of the online validation period, six were found dead, five had to be euthanized (due to bad body condition and severe suffering with no prospects of recovery) and 10 pigs were removed from the trial for welfare reasons (attacked by other pigs, severely lame, very bad body condition, etc.). Of the removed pigs, most also had to be euthanized later on, because they did not recover.

A variety of problems occurred and several treatments were necessary. In total, nine ear tags were lost on seven pigs. Lost ear tags were replaced as soon as possible. The ADG between two weight measurements was below 0.40 kg per day 134 times, spread across 96 pigs. Of these 134 occurrences, an ADG < 0.25 kg was measured 52 times for 43 pigs in total. During the first two weeks after introduction in the pens, the ADG was only 0.34 kg per day for the entire barn, 83 pigs grew less than 0.40 kg per day and 26 of these pigs grew even less than 0.25 kg. As mentioned in Table 1, during the first two weeks only the pigs with an ADG < 0.25 kg were considered to have an orange or red status.

After removal of days with technical problems and pigs that were no longer in the barn, a total of 14 634 pig-measurement days remained. Of these pig-days, 12 709 had status green assigned to them, while 1 380 were given status orange and 545 days received status red. During one weekend (day 68-69) a lot of alerts were given by the system, after checking these pigs on Monday, a lot of pigs had high temperatures or even fever, but they were recovering. Suspected was that there was a health problem in the groups during the weekend and this weekend was considered status orange for all pigs. Excluding this weekend, only 20 pigs received the status green across the entire fattening period. One hundred and eight pigs received at least one orange status, while the red status was spread across 98 pigs, with 86 pigs receiving at least one orange and red status.

3.2.2 Performance of the warning systems applied online

The overall performance of the four warning systems applied online during the validation period is summarized in Table 3, together with the performance for the different statuses separately (green, orange, red). For the SGC avIVI, no alerts are generated during the reference-period of five days to initialise the model and control limits. Any missed problems during that period count as FN for the SGC avIVI. For SGC # reg, alerts were generated the first five days because of the added fixed limit. The SGC methods have a better overall performance than the use of a fixed limit for both variables. Specificity and accuracy are always high. However, to be useful in practice, the sensitivity and precision of the system should also be high. The number of missed problems and the number of false alerts should be minimal. If sensitivity and specificity are considered equally important, SGC # reg is the best performing control chart.

Sensitivity was higher for days with a red status than for days with an orange status (e.g. 27.7 percentage points higher for SGC # reg). Severe problems are thus better detected than mild problems. Note that some orange days are also due to the ADG < 0.40 kg, which cannot be attributed to a single problem day, but was instead attributed to the entire two weeks between weight measurements. As it is likely that for some pigs the productivity problem was in reality not equally spread or present across the entire two weeks, it is also likely that the feeding pattern was normal during some of those orange days. This could also partially explain the lower sensitivity for the days with an orange status.

The average run lengths of the SGC # reg were also calculated (

	Performance of warning systems applied online			
	Fixed limit # reg	**Fixed limit avIVI**	**SGC # reg**	**SGC avIVI**
Sensitivity [%]	48.5	22.1	58.0	41.5
Specificity [%]	99.0	99.2	98.7	99.1
Accuracy [%]	96.6	96.1	96.7	96.4
Precision [%]	71.2	54.6	71.1	69.8
# alerts	475	240	609	407
TP	338	131	433	284
FP	137	109	176	123
TN	13 800	13 931	13 711	13 827
FN	359	463	314	400
% alerts on days with				
green status	28.8	45.4	28.9	30.2

orange status	32.0	20.4	33.2	34.2
red status	39.2	34.2	37.9	35.6
Sensitivity [%] for days with				
orange status	11.0	3.6	14.6	10.1
red status	34.1	15.0	42.4	26.6

Table **4**). Note that since an alert for the data of a certain measurement day could only be generated the next day (when 24 h of data were collected); the ARL_1 was always minimum one day.

3.2.3 Detailed results on specific cases

Specific cases are shown to illustrate the warning systems. First an example of a good detection is shown, then the FP and FN of the SGC # reg are analysed and the pigs with the most FP and FN are shown in more detail.

In

Average run lengths of SGC # reg	
	False alerts
Average # of FP per day	1.5
Average # of FP per pig	1.3
ARL_0 = average time till first false alert (days)	101.0

	Detection of all red blocks (*n* = 213)	**Detection of red blocks > 1 day (*n* = 90)**
% of red blocks detected	40.8	64.4
% of positive detections on first day of process shift	89.7	84.5
ARL_1 = average speed of detection (days)	1.3	1.4

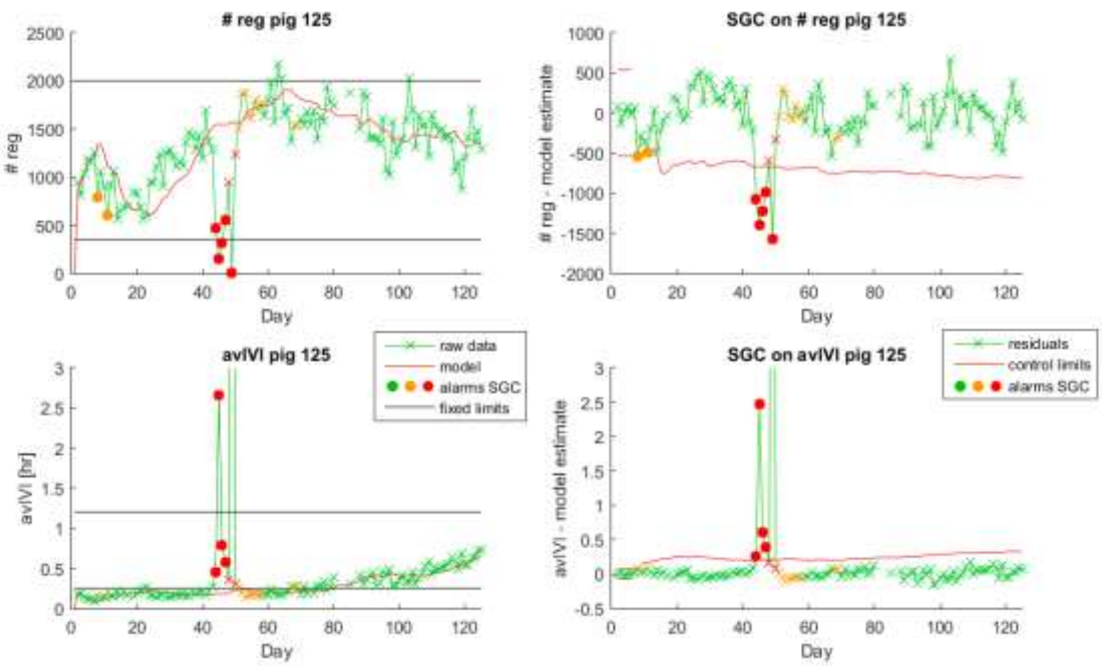


Figure **2** the results of the warning systems are illustrated for **pig 125**. This pig has two orange days at the beginning of the period (thin and longer hair; new mild lameness). Between day 44 and day 50, the pig was seen with severe lameness, fever, reduced activity and thin flanks and was thus assigned status red. Afterwards, the pig recovered (mild lameness for another three days and then no longer lame), but another eight days were status orange due to ADG of 350 g measured at day 58. The # reg was < 350 for three days, resulting in 3 TP and 4 FN for the fixed limit # reg. The fixed limit avIVI only detected two problem-days (2 TP, 5 FN). Performance is better for SGC avIVI (5 TP, 2 FN), but SGC # reg performed the best, with seven problem-days detected and only two missed. This pig was not noticed by the caretakers and not treated, but did have a serious problem that affected its welfare and productivity (ADG was reduced that period to 0.35 kg compared to 0.69 kg on average over the entire period). The fact this pig has a problem, was however, successfully detected by the warning systems.

For the method SGC # reg the **FP** were analysed in more detail. In total 176 of the 609 alerts were false. These false alerts were spread across 30 pigs. Pig number 133 had the most false alerts, 47 in total. Other pigs with a large number of false alerts were pig 1 (17 FP), pig 39, 82 and 120 (each 14 FP).

The # reg throughout the fattening period and the corresponding control chart for **pig 133** are shown in Figure 3. As can be seen, all false alerts were due to the daily # reg being lower than 350 (so crossing the fixed limit). This pig was usually set at status green as no clear indications were present that pointed towards health or welfare problems, except some coughing and stiffness. Five days were set at status red and five days had status orange due to mild lameness on two legs, fever, the weekend with possible health problems in the entire barn, or lost tags (resulting in 8 TP and 2 FN). The pig was, however, not lively nor active and internal abscesses were found in the slaughterhouse. It was also amongst the smallest and slowest growing pigs in the barn (end weight of 89 kg and ADG of 560 g).

The FP for pig 1 and pig 120 were due to the # reg being lower than 350 for a longer period of time after a period of problems. It is important to notice that pig 1 and pig 133 were the only pigs in the barn having floppy, hanging ears throughout the fattening period. This could hinder the registrations as the RFID ear tags would be closer to the ground and thus further from the

RFID antenna during feeding than for other pigs (Maselyne et al., 2014a; Maselyne et al., 2014b). If these two pigs (1 and 133) would be identified as poor performing outliers and excluded from the analysis, the precision of SGC # reg would increase to 79.4 %.

Pig 39 suddenly dropped its level of feeding (from > 2000 reg to around 1500 reg), which made the registered feeding pattern cross the control limit of the SGC # reg. These FP for pig 39 might be related to the change of antenna height, as the FP started at day 95, and the height of the antenna in that pen was changed at day 94. However, no other examples of periods of FP directly following the change of antenna height were found. The pen-averages of the validation period (data not shown) show a small decrease in the # reg around the time that the height of the antennas was increased (day 92 or 94), but this effect was much smaller than for the pen-averages in the historical dataset (data not shown, 38% of the pigs affected, see section 3.1.1).

The 314 **FN** for SGC # reg were also analysed. These missed problems were spread across 87 pigs. Pig number 87 had the most FN (20 FN), directly followed by pig 72 (19 FN) and pig 68 and 84 (15 FN).

The # reg throughout the fattening period and the corresponding control chart for **pig 87** (end weight of 90.5 kg with an ADG of 520 g) are shown in Figure 4. The observers noticed soon after the start of the fattening period that this pig had severe diarrhoea and was thin with a convex back (red status day 7-8, 16). The pig subsequently showed severe thin flanks and lameness at day 28 (red status). All other days between day 1 and 27, it had an orange status as the ADG was 0.17 kg at day 1-16 and -0.03 kg at day 17-30. The red status continued from day 28 until day 39 with the pig also showing fever, coughing and signs of nerve symptoms or paralysis (had difficulties to use its hind legs, fell over often as a consequence). The veterinarian stated that the latter could be a sign of pressure on the nerves in the spine and the pig was treated once with an anti-inflammatory and analgesic agent (day 29) and twice with antibiotics (day 29 and 35). From day 40 onwards the pig's condition was improved (mild lameness, active; orange status day 40-45) and the observers noticed an abscess becoming visible at the pig's back. The pig also had some days with fever and thin flanks later on when the abscess was open (open wound) and other abscesses appeared (day 70, 77-80), leading to in total 20 days with status red. However, the SGC # reg did not give an alert for pig 87 (20 FN). An explanation for this can be found in the large variation in the feeding pattern during the reference period, which lead to wide initial control limits, while the problem started directly after the reference period. There is a drop in the feeding pattern visible, but as this occurs gradually and early in the period, the model follows the data and the control chart is not able to detect the process shift in this case. Similar observations are noted for example for pig 72, 68 and 84.

4 Discussion

The overall best performing warning system was the Synergistic Control method on the number of registrations (SGC # reg). This system had a sensitivity of 58.0 %, specificity of 98.7 %, accuracy of 96.7 % and precision of 71.1 %. The average time until a first false alert was 101.0 days (in-control average run length ARL_0) and severe problems were detected within 1.3 days on average (out-of-control average run length ARL_1).

These results are promising and are in line with the results for other warning systems reported in literature. Huybrechts et al. (2014) reported a sensitivity of 63 % for detecting mastitis based on measurements of the milk yield of dairy cows and using SGC methods. This was with a cusum control chart set at an ARL_0 of 156 milkings, which corresponded to 60 days. On average, clinical mastitis was detected by the control chart one milking before the farmer detected it and up to four days (eight milkings) in advance in the best case (Huybrechts et al., 2014). Quimby et al. (2001) used a cusum control chart to predict morbidity of calves using records of their feeding behaviour. They reported an overall accuracy, precision and sensitivity of 87 %, 91 % and 90 %, respectively. The cusum procedure detected animal morbidity 3.7 to 4.5 days earlier than the feedlot personnel (Quimby et al., 2001). Kruse et al. (2011) used wavelet analysis to identify water intake variation in sows due to health problems and to differentiate between healthy and treated sows. They reported sensitivities ranging from 34 % to 83 % and specificities ranging from 32 % to 92 %. For example, a sensitivity of 49.7 % corresponded to a specificity of 76.9 % and an error rate of 73.9 % (or a precision of 26.1 %) (Kruse et al., 2011). Some other reports on warning systems only present cases and do not report any performance measures (for example Engler et al., 2009; Madsen and Kristensen, 2005; Mertens et al., 2008).

To establish the performance of the warning systems, a 'golden' standard should be available for comparison. For health and welfare problems, no real golden standard exists. In most papers discussed above, the alerts were validated by comparing them to the farmers' logbooks of treatments (Huybrechts et al., 2014; Quimby et al., 2001). This approach allows to calculate whether the warning systems were able to detect problems earlier than the farmer, but it does not guarantee that no 'real problems' are missed. For the analysis performed in this study, treatments by the caretakers were used to compare with the alerts for the historical dataset. However, this might not perfectly represent the true problem status of the barn, as the status of treated pigs was not followed up before and after treatment. Also, the monitoring time per pig is very low. Reported times spent performing a livestock check by pig farmers are between 3.6 and 6 s per pig per day (Heitkämper et al., 2011; van den Heuvel et al., 2004), corresponding to maximum 14 min for the entire barn.

Since there were no data available on the number of problems that are missed by the farmers or caretakers, evaluation was based on detailed visual monitoring by two observers (during several hours) during the online validation period. This monitoring was made as objective as possible by using the criteria established in Table 1 and the clinical assessment check-list and multiple scoring systems. These were formulated in close collaboration with a veterinarian. In addition to the visual monitoring by the observers (and the caretakers), the entire barn was also checked by a veterinarian every two weeks. By checking the alerts of the systems daily, a possible bias may be present in the observations. To reduce this effect, all the pigs were checked first per pen before the specific pigs with an alert were checked again in more detail. Since the performance was calculated per day, the timing of the problems was also taken very strictly. If a problem was observed on one day, but not on the next day, an alert for the second day was considered false. However, it is possible that the problem was still present during part of the day. Single days with a red status were left red, although it can be questioned whether this was really a severe problem as it lasted only one day. However, the duration of the problem was not known the first day it was noticed. In general, even with extensive daily observations it is not easy to determine the exact health status of each pig on a daily basis.

For productivity problems weight measurements can be used. These measurements are objective, but the weight of a pig can vary throughout the day (e.g. before or after a meal or drinking bout for example). A second difficulty with weight data is that they are not gathered daily, but only every couple of weeks, which makes it difficult to compare to the daily alerts. Here, the choice was made to give a status orange during the entire period between weight measurements in case of low growth, but it is not certain that the problem was present all the time. However, this choice, and the use of orange days in general, does have an effect on the calculated performance. Since orange days are considered always a true positive or true negative, the more orange days are present, the higher the performance will often be. No better way to deal with these mild problems was found.

The development of a good warning system starts with good measurement data. Therefore, the registrations of the RFID system were previously validated and range measurements were performed (Maselyne et al., 2014a; Maselyne et al., 2014b). A drawback that was found is that the performance of the measurement system can be influenced by the behaviour of individual pigs (lying down during feeding for example). However, this is not necessarily an issue for problem detection through the detection of changes in individual pigs' feeding patterns, if this behaviour is consistent throughout time (Maselyne et al., 2014a). Also changing the height of the RFID antennas half-way through the fattening period was necessary to ensure good registrations of young, small piglets and comfort for the larger, older pigs (Maselyne et al., 2014b). However, this can cause an abrupt change in the measured feeding patterns. This was noticed during the fattening period of the historical dataset, but was not that obvious during the online validation period (see section 3.2.3). This could be because the pigs were older during the online validation period when the height of the antennas was changed (92-94 days in the pens versus 78 days in the pens in the historical dataset). To avoid this unwanted influence on the measurement data and to make the system more practical it is recommended to investigate alternative solutions for this problem, such as automatically and gradually changing the height or adapting the antenna so it works for all situations.

Feeding behaviour can be expressed using several units (registrations, feeding visits, meals) and for each unit also several variables are possible (number, duration, interval) (Maselyne et al., 2015). Here, the choice was made to monitor the number of registrations (which is correlated with observed feeding duration (Maselyne et al., 2014a; Maselyne et al., 2016)) and the average interval between feeding visits. To construct the feeding visits, an objectively determined visit criterion was used (Maselyne et al., 2016). Also other choices of variables could have been made to represent the real feeding behaviour, e.g. the duration of feeding visits (Maselyne et al., 2016). The large amount of data gathered during the online validation period allows to investigate the potential of alternative variables. In the present study, the number of registrations showed a sudden decrease after the first days in the pen and a recovery afterwards (see section 3.1.1). Possible explanations for this 'dip' in the number of registrations could be aggression, stress, coping difficulties or infection pressure related to the new barn and new pen-mates. The increase in registrations afterwards could be due to increased age, increased coping abilities with the new environment, but also increased size of the pigs (closer to the antenna, thus possibly better registrations). The average interval between feeding visits increased towards the end of the fattening period, which is possibly an age-effect.

Finally, also the design of the warning system influences its performance. Both fixed limits and time-varying, individual control limits (established using the method of Synergistic Control) were tested. Several researchers reported that the feeding pattern of pigs varied between individual pigs and through time (Brown-Brandl et al., 2013; Hessel and Van den Weghe, 2011; Maselyne et al., 2014a). The same results were found here (see for example Figure 1). Due to this large inter- and intra-individual variation, fixed limits were less suited to detect changes in individual pigs' feeding patterns and individualized monitoring could be more successful (Viazzi et al., 2013). Indeed, the best performing method was the Synergistic Control method applied to the number of registrations.

It should be noted that the performance calculated for the historical dataset only gives an indication and is not complete. Only precision and problem detection rate were calculated, with alerts assigned to problems if close enough or preceding the treatment. No sensitivity per day could be calculated, as no daily observations of the pig's status were available (only treatments, and possible repetitions of treatments after a couple of days). Instead, an estimated sensitivity was calculated as the number of true alerts divided by the sum of true alerts and the number of problems that were not detected. However, this is a distorted measure which overestimates the true sensitivity, as problems that are not detected were counted as one problem, while detected problems were counted by the number of true alerts (possibly > 1).

The performance for the warning systems during the online validation period was quantified more completely in terms of sensitivity, specificity, accuracy, precision and average run lengths (Table 3 and

	Performance of warning systems applied online			
	Fixed limit # reg	**Fixed limit avIVI**	**SGC # reg**	**SGC avIVI**
Sensitivity [%]	48.5	22.1	58.0	41.5
Specificity [%]	99.0	99.2	98.7	99.1
Accuracy [%]	96.6	96.1	96.7	96.4
Precision [%]	71.2	54.6	71.1	69.8
# alerts	475	240	609	407
TP	338	131	433	284
FP	137	109	176	123
TN	13 800	13 931	13 711	13 827
FN	359	463	314	400
% alerts on days with				
green status	28.8	45.4	28.9	30.2
orange status	32.0	20.4	33.2	34.2
red status	39.2	34.2	37.9	35.6
Sensitivity [%] for days with				
orange status	11.0	3.6	14.6	10.1
red status	34.1	15.0	42.4	26.6

Table **4**), calculated based on a comparison with the observations. The observers spent much more time in the stable than a farmer would have. So, it is most likely that the observers spotted more problems and spotted the problems also earlier. The observations also included information that an average pig farmer would not collect, such as regular weight measurements and rectal temperatures. Additional research is recommended to also compare the performance of the warning systems with today's monitoring by a farmer. It should also be investigated which performance measure (sensitivity, specificity, precision, etc.) and which problems are most important for a pig farmer. This would allow to adapt the warning systems better to the needs of the pig farmers.

False alerts may be attributed to a combination of measurement errors (pig not registered properly), faults in the warning system (too narrow control limits or model not following the data properly), a changed feeding pattern due to other influences (e.g. environment, social ranking, stress) or subclinical problems that were not noticed by the observers. Problems could be missed due to faults in the warning system (too wide control limits), due to the lack of sensitivity for small process shifts (problem occurring gradually, see for example Figure 4) or when the pig recovers from a problem and appears to be feeding again, but the symptoms are still present (this was also counted as false negatives). Another reason for missed problems could be that the feeding pattern variable did not change during the problem. Either the change might be visible in other variables of the feeding pattern (e.g. same number of registrations, but more at night) or the feeding pattern was still the same. To increase performance, the Shewhart control chart could be replaced or supplemented with a cusum control chart in further research, as a cusum control chart can be more successful in detecting small, gradual process shifts (Montgomery, 2009). Also, combination of several variables into one warning system or multivariate analysis might increase the performance (De Ketelaere et al., 2011).

Critical evaluation of the obtained performance values leads to the question whether problem detection based on the feeding pattern would be useful for the farmer. Pigs were found to sometimes recover without any attention from the caretakers or treatments (for example pig 125,

Average run lengths of SGC # reg		
	False alerts	
Average # of FP per day	1.5	
Average # of FP per pig	1.3	
ARL_0 = average time till first false alert (days)	101.0	
	Detection of all red blocks (*n* = 213)	**Detection of red blocks > 1 day (*n* = 90)**
% of red blocks detected	40.8	64.4
% of positive detections on first day of process shift	89.7	84.5
ARL_1 = average speed of detection (days)	1.3	1.4

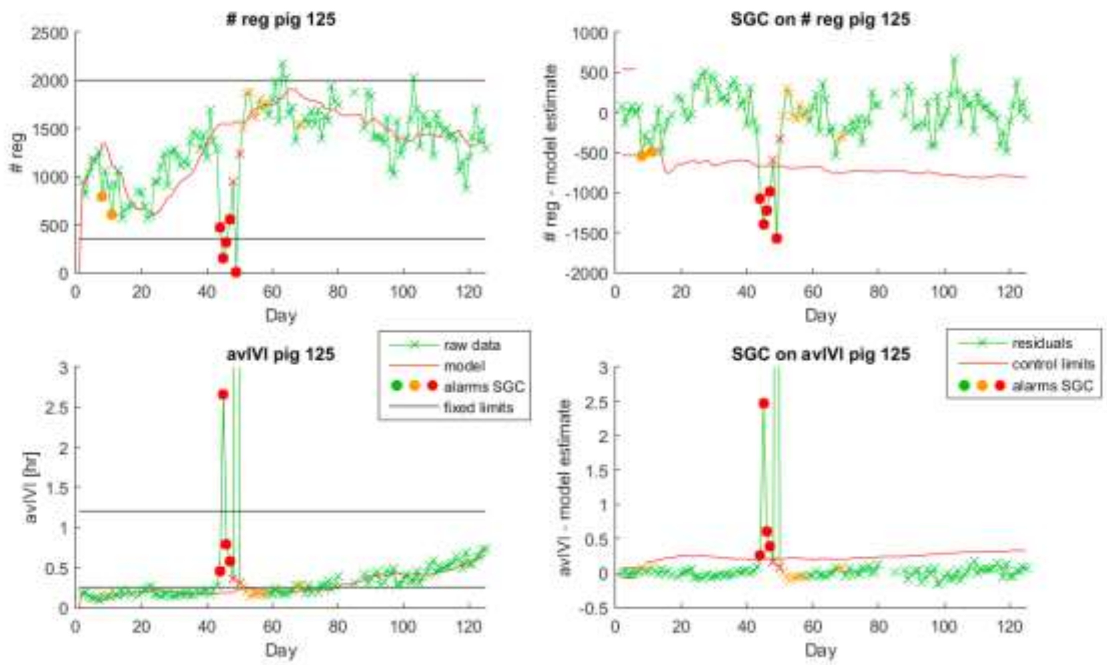


Figure **2**). However, these problems could easily affect the productivity (as was also the case for pig 125). Although the detected problems might not always correspond to necessary treatments, it is important that all pigs with welfare, health and productivity issues are brought to the attention of the farmer, such that each individual case can be properly evaluated. The measured feeding patterns also bring a lot of extra information to the farmer. A pig with clinical symptoms, but which is still feeding often might be better off than a pig with the same symptoms, but a reduced feeding level.

Conclusion

To detect problems in individual fattening pigs, warning systems were developed to detect changes in the feeding patterns of individual fattening pigs pointing towards health, welfare and productivity problems. The individual feeding patterns were measured using an RFID system at the feeder trough. Both fixed limits (one threshold for all pigs and days) and individual, time-varying limits constructed using Synergistic Control were developed. The best performance was achieved for the Synergistic Control method on the number of RFID registrations per pig. Large inter- and intra-individual variation is present in the feeding pattern of individual pigs, justifying an individual monitoring approach. The obtained performance of the warning system is considered promising, but further improvements are still possible especially for the sensitivity and the precision. False alerts reduce the farmer's confidence in the system and for optimal pig health, welfare and performance the majority of problems should be detected. If the performance is further improved, the online warning system could make a valuable and objective tool that can help the farmer to monitor its pig herd and make well-funded management decisions, while improving the health, welfare and productivity of the pigs.

Acknowledgments

Jarissa Maselyne has been funded by a PhD grant from the Agency for Innovation by Science of Technology (IWT Flanders – project SB 111447). The authors would like to thank Liesbet Pluym, Annelies Michiels and Liesbeth De Wilde for their help during this study. Special thanks also go to the technical staff of ILVO for the work and technical support provided and to the animal caretakers for their daily care of the pigs.

References

Banhazi, T. M., Lehr, H., Black, J. L., Crabtree, H., Schofield, P., Tscharke, M., & Berckmans, D. (2012). Precision livestock farming: An international review of scientific and commercial aspects. *International Journal of Agricultural and Biological Engineering, 5,* 1-9.

Brown-Brandl, T. M., Rohrer, G. A., & Eigenberg, R. A. (2013). Analysis of feeding behavior of group housed growing-finishing pigs. *Computers and Electronics in Agriculture, 96*, 246-252.

Cornou, C. & Kristensen, A. R. (2013). Use of information from monitoring and decision support systems in pig production: Collection, applications and expected benefits. *Livestock Science, 157*, 552-567.

De Ketelaere, B., Mertens, K., Mathijs, F., Diaz, D. S., & De Baerdemaeker, J. (2011). Nonstationarity in statistical process control - issues, cases, ideas. *Applied Stochastic Models in Business and Industry, 27*, 367-376.

Engler, J., Tölle, K. H. , Timm, H. H., Hohls E., & Krieter, J. (2009). Control charts applied to pig farming data. *Archiv fur Tierzucht-Archives of Animal Breeding, 52*(3), 272-283.

Hart, B. L. (1988). Biological basis of the behavior of sick animals. *Neuroscience & Biobehavioral Reviews, 12*, 123-137.

Heitkämper, K., Schick, M., & Fritzsche, S. (2011). Working-time requirement in pig fattening. *Landtechnik, 66,* 113-115.

Hessel, E. F., & Van den Weghe, H. F. A. (2011). Individual online-monitoring of feeding frequency and feeding duration of group-housed weaned piglets via high frequent radiofrequency identification (HF RFID). *Papers presented at the 5th European Conference on Precision Livestock Farming EC PLF 2011*, Prague, Czech Republic: 210-222. Editors: Lokhorst C., & Berckmans D.

Hulsen, J., & Scheepens, K. (2005). Varkenssignalen: praktijkgids voor diergericht varkenshouden. Roodbont Uitgeverij, ISBN 90-75280-53-X.

Huybrechts, T., Mertens, K., De Baerdemaeker, J., De Ketelaere, B., & Saeys, W. (2014). Early warnings from automatic milk yield monitoring with online synergistic control. *Journal of Dairy Science, 97,* 3371-3381.

Kruse, S., Traulsen, I., Salau, J., & Krieter, J. (2011). A note on using wavelet analysis for disease detection in lactating sows. *Computers and Electronics in Agriculture, 77*, 105-109.

Madsen, T. N., & Kristensen, A. R. (2005). A model for monitoring the condition of young pigs by their drinking behaviour. *Computers and Electronics in Agriculture, 48,* 138-154.

Maselyne, J., Saeys, W., & Van Nuffel, A. (2015). Review: Quantifying animal feeding behaviour with a focus on pigs. *Physiology & Behavior, 138,* 37-51.

Maselyne, J., Saeys,, W., Briene, P., Mertens, K. C., Vangeyte, J., De Ketelaere, B., Hessel, E. F., Sonck, B., & Van Nuffel, A. (2016). Methods to construct feeding visits from RFID registrations of growing-finishing pigs at the feeder trough. *Computers and Electronics in Agriculture*, *128*, 9-19.

Maselyne, J., Saeys, W., De Ketelaere, B., Mertens, K., Vangeyte, J., Hessel, E. F., Millet, S., & Van Nuffel, A. (2014a). Validation of a High Frequency Radio Frequency Identification (HF RFID) system for registering feeding patterns of growing-finishing pigs. *Computers and Electronics in Agriculture, 102,* 10-18.

Maselyne, J., Van Nuffel, A., De Ketelaere, B., Vangeyte, J., Hessel, E. F., Sonck, B., & Saeys, W. (2014b). Range measurements of a High Frequency Radio Frequency Identification (HF RFID) system for registering feeding patterns of growing-finishing pigs. *Computers and Electronics in Agriculture*, *108*, 209-220.

Matthews, S. G., Miller, A. L., Clapp, J., Plötz, T., & Kyriazakis, I. (2016). Early detection of health and welfare compromises through automated detection of behavioural changes in pigs. *The Veterinary Journal, 217,* 43-51.

Mertens, K., Decuypere, E., De Baerdemaeker, J., & De Ketelaere, B. (2011). Statistical control charts as a support tool for the management of livestock production. *Journal of Agricultural Science*, *149*, 369-384.

Mertens, K., Vaesen, I., Loffel, J., Kemps, B., Kamers, B., Zoons, J., Darius, P., Decuypere, E., De Baerdemaeker, J., & De Ketelaere, B. (2009). An intelligent control chart for monitoring of autocorrelated egg production process data based on a synergistic control strategy. *Computers and Electronics in Agriculture*, *69*, 100-111.

Mertens, K., Vaesen, I., Loffel, J., Ostyn, B., Kemps, B., Kamers, B., Bamelis, F., Zoons, J., Darius, P., Decuypere, E., De Baerdemaeker, J., & De Ketelaere, B. (2008). Data-based design of an intelligent control chart for the daily monitoring of the average egg weight. *Computers and Electronics in Agriculture, 61*, 222-232.

Michiels, A., Piepers, S., Ulens, T., Van Ransbeeck, N., Sacristan, R. D. P., Sierens, A., Haesebrouck, F., Demeyer, P., & Maes, D. (2015). Impact of particulate matter and ammonia on average daily weight gain, mortality and lung lesions in pigs. *Preventive Veterinary Medicine, 121*, 99-107.

Montgomery, D. C. (2009). *Introduction to Statistical Quality Control*. (6^{th} ed.). Hoboken, USA, John Wiley & Sons, Inc.

Morrison, R. B., Hilley, H. D., & Leman, A. D. (1985). Comparison of Methods for Assessing the Prevalence and Extent of Pneumonia in Market Weight Swine. *Canadian Veterinary Journal-Revue Veterinaire Canadienne, 26,* 381-384.

Quimby, W. F., Sowell, B. F., Bowman, J. G. P., Branine, M. E., Hubbert, M. E., & Sherwood, H. W. (2001). Application of feeding behaviour to predict morbidity of newly received calves in a commercial feedlot. *Canadian Journal of Animal Science, 81,* 315-320.

Telkanranta, H., Bracke, M. B. M., & Valros, A. (2014). Fresh wood reduces tail and ear biting and increases exploratory behaviour in finishing pigs. *Applied Animal Behaviour Science, 161,* 51-59.

van den Heuvel, E. M., Hoofs, A. I. J., Binnendijk, G. P., Bosma, A. J. J., & Spoolder, H. A. M. (2004). Grote groepen vleesvarkens. Effects of group size on fattening pigs. *Praktijkrapport Varkens 29*. Lelystad, the Netherlands, Wageningen UR.

Viazzi, S., Bahr, C., Schlageter-Tello, A., Van Hertem, T., Romanini, C. E. B., Pluk, A., Halachmi, I., Lokhorst, C., & Berckmans, D. (2013). Analysis of individual classification of lameness using automatic measurement of back posture in dairy cattle. *Journal of Dairy Science, 96*, 257-266.

Wathes, C. M., Kristensen, H. H., Aerts, J. M., & Berckmans, D. (2008). Is precision livestock farming an engineer's daydream or nightmare, an animal's friend or foe, and a farmer's panacea or pitfall? *Computers and Electronics in Agriculture*, *64*, 2-10.

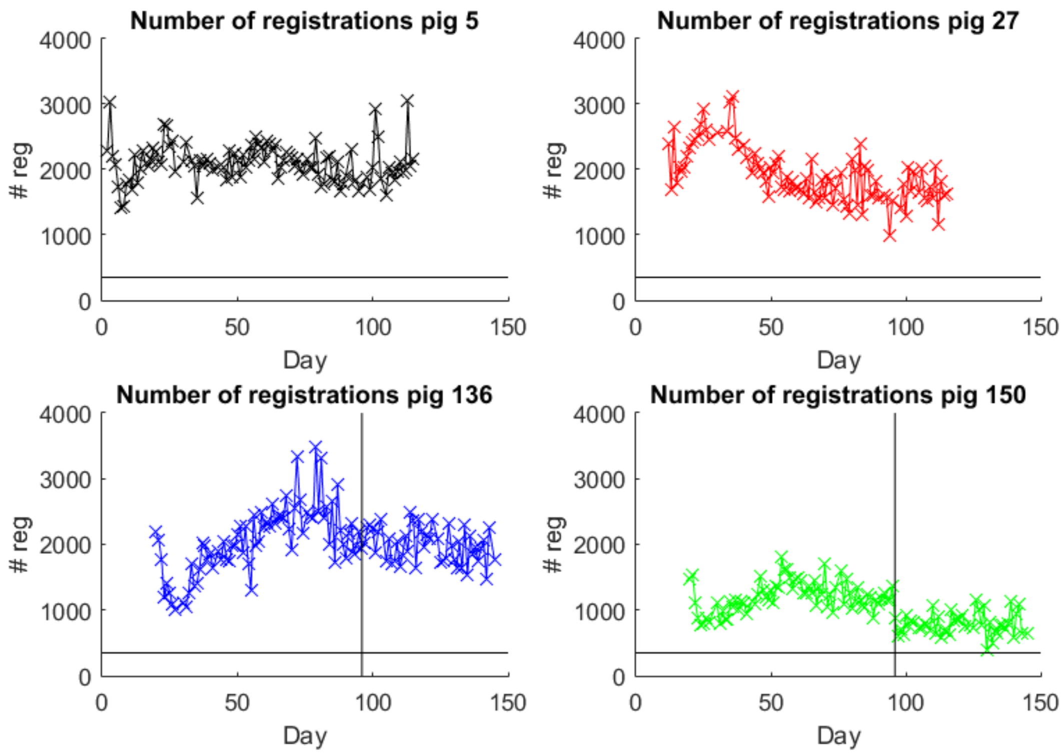
Welfare Quality® (2009). *Welfare Quality® Assessment Protocol for Pigs*. Lelystad, Netherlands, Welfare Quality® Consortium.

Table and Figure Captions

Table 1: Criteria to determine the daily status of each pig (green – no problem, orange – mild problem or red – severe problem) in the online validation round, based on expert observations.

Status pig	**Alert**	**No alert**	**Criteria for status**
Green = no problem (*n* = 12 907)	FP	TN	• No problem noticed • Single problems such as cough, small wound or swelling on the tail, stiffness, scratches
Orange = mild problem (*n* = 1 182)	TP	TN	• Fever ≥ 40° and < 40.5° in the first three weeks • Mild lameness: new or on more than one leg • Severe infection of the tail • Purple ears • Combination of two problems (like mild lameness, thin, reduced activity, diarrhoea, abscesses or open wound) • Entire two weeks if ADG < 400 g (< 250 g during the first two weeks)
Red = severe problem (*n* = 545)	TP	FN	• Death • Lost ear tag • Fever > 40° (≥ 40.5° in the first three weeks, ≥ 40.3° during weighing) • Nerve symptoms, paralysis • Heavy and rapid breathing • Severe lameness • Any problem + severe infection of the tail (or new) • Any problem + thin flanks

			• One day if ADG < 400 g (not during the first two weeks) • Two days if ADG < 250 g



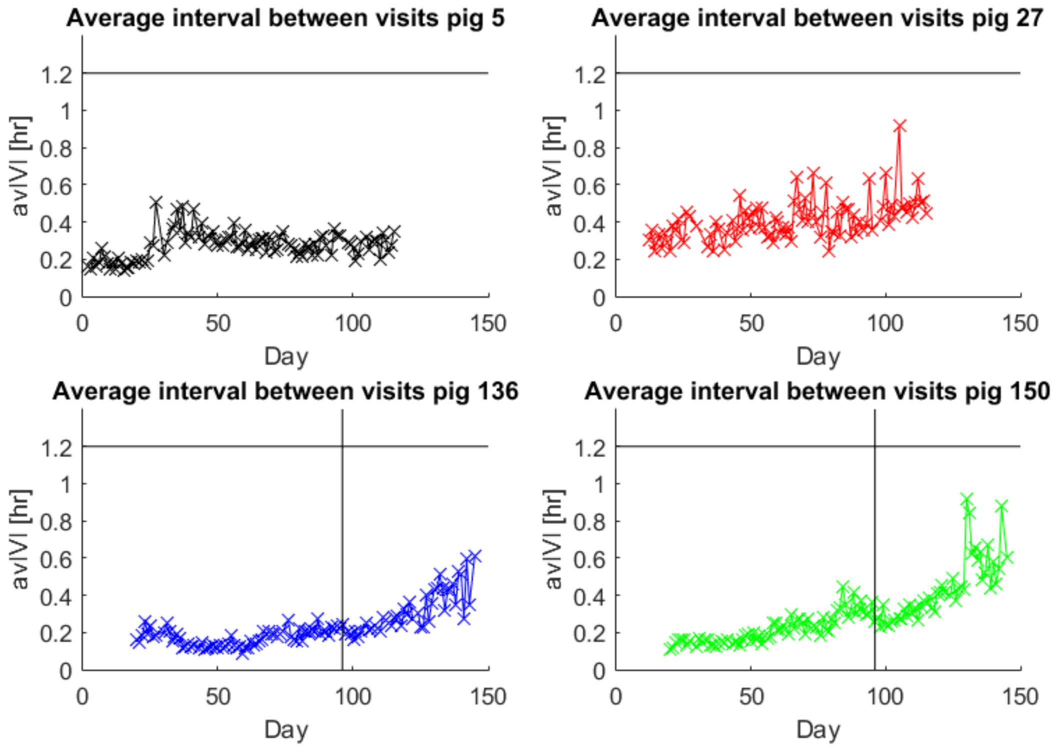


Figure 1: (a) Number of registrations (# reg) and (b) average interval between feeding visits (avIVI) for four healthy pigs in the historical dataset. Horizontal black lines represent the fixed limits (# reg < 350 and avIVI > 1.2 hr). Vertical black lines represent the day that the antenna height was changed in pen 2 and 3.

Table 2: Details of the four warning systems used during the online validation period and developed based on the historical dataset.

Method	**Details**
Fixed limit # reg	Fixed limit on the number of registrations: - Alert if # reg < 350
Fixed limit avIVI	Fixed limit on the average inter-visit interval: - Alert if avIVI > 1.2 hr
SGC # reg	Synergistic Control on the number of registrations: - Linear regression model, sliding window 30 days - Shewhart chart with $LCL = -4\ \overline{MR}$ - No alert if # reg ≥ 2000 - Alert if # reg < 350
SGC avIVI	Synergistic Control on the average inter-visit interval: - Linear regression model, sliding window 30 days - Shewhart chart with $UCL = \ 6\ \overline{MR}$ - No alert if avIVI < 0.25 hr

Table 3: Performance of the warning systems for the online validation period, in total and split up per status (green, orange or red, see Table 1). See Table 2 for a description of the warning systems applied online.

	Performance of warning systems applied online

	Fixed limit # reg	**Fixed limit avIVI**	**SGC # reg**	**SGC avIVI**
Sensitivity [%]	48.5	22.1	58.0	41.5
Specificity [%]	99.0	99.2	98.7	99.1
Accuracy [%]	96.6	96.1	96.7	96.4
Precision [%]	71.2	54.6	71.1	69.8
# alerts	475	240	609	407
TP	338	131	433	284
FP	137	109	176	123
TN	13 800	13 931	13 711	13 827
FN	359	463	314	400
% alerts on days with				
green status	28.8	45.4	28.9	30.2
orange status	32.0	20.4	33.2	34.2
red status	39.2	34.2	37.9	35.6
Sensitivity [%] for days with				
orange status	11.0	3.6	14.6	10.1
red status	34.1	15.0	42.4	26.6

Table 4: Average run lengths of the best performing warning system SGC # reg. ARL's are averaged across all pigs. Red blocks are all uninterrupted blocks of days with a red status.

Average run lengths of SGC # reg

	False alerts	
Average # of FP per day	1.5	
Average # of FP per pig	1.3	
ARL_0 = average time till first false alert (days)	101.0	
	Detection of all red blocks (*n* = 213)	**Detection of red blocks > 1 day (*n* = 90)**
% of red blocks detected	40.8	64.4
% of positive detections on first day of process shift	89.7	84.5
ARL_1 = average speed of detection (days)	1.3	1.4

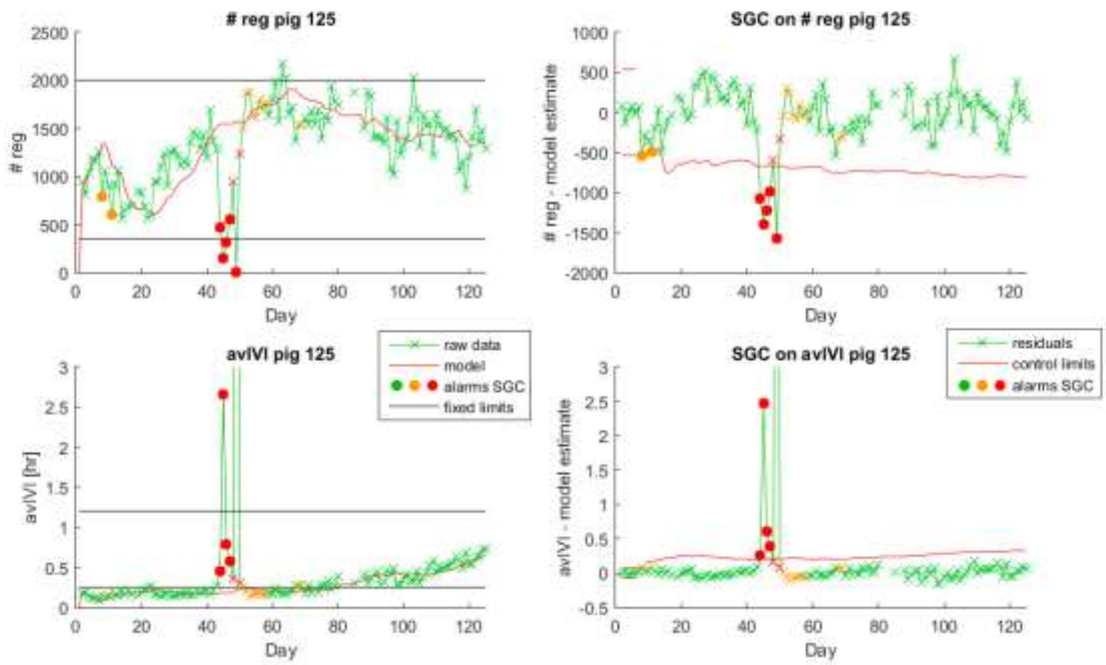


Figure 2: Example of the warning systems for the data of pig 125. Left: the raw data (# reg or avIVI [hr]), the fixed limits and the linear regression model estimate and sensitizing rules for the SGC methods, Right: residuals (raw data minus model estimate) and the control limits for the SGC methods. Dots are the alerts for the SGC # reg or the SGC avIVI. Alerts for the fixed limits can easily be deduced from the left figure (Table 2). Colours of the crosses and dots indicate the pig-status: green = status green; orange = status orange, red = status red. Point outside the graph in the bottom plots is for 12 hr avIVI on day 49, which also gives an alert for SGC avIVI.

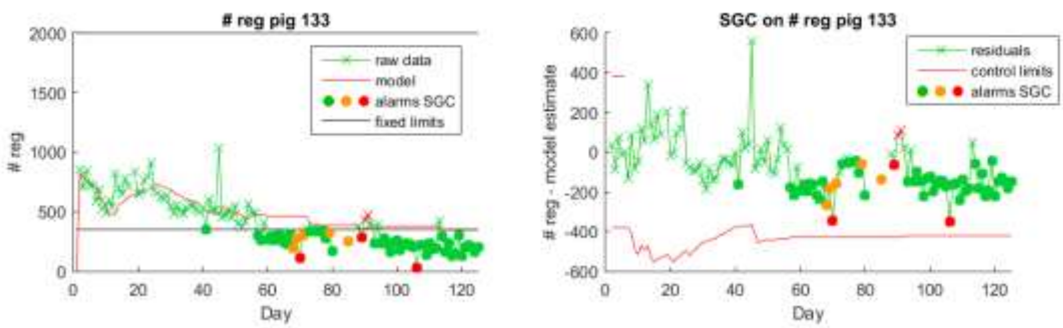
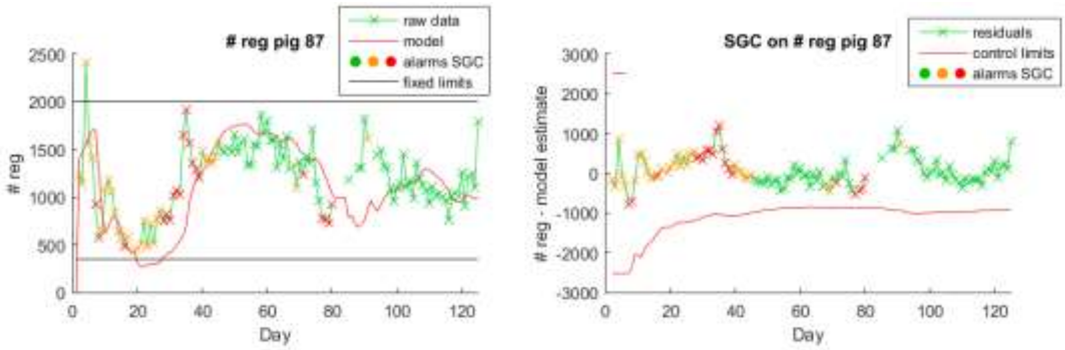


Figure 3: Example of the SGC # reg for the data of pig 133. Left: the raw data (# reg), the linear regression model estimate and the sensitizing rules, Right: residuals (raw data minus model

833 estimate) and the control limits. Dots are the alerts for the SGC # reg (Table 2). Colours of the

834 crosses and dots indicate the pig-status.



835

836 Figure 4: Example of the SGC # reg for the data of pig 87. Left: the raw data (# reg), the linear

837 regression model estimate and the sensitizing rules, Right: residuals (raw data minus model

838 estimate) and the control limits (Table 2). Colours of the crosses indicate the pig-status.