LANDTECHNIK 74(3), 2019, 55–68
DOI:10.15150/lt.2019.3204
LANDTECHNIK
AGRICULTURAL ENGINEERING

Evaluation of a dung-removal robot for use in dairy housing from an ethological and process-engineering point of view

Theresa Leinweber, Michael Zähner, Sabine Schrade

To date, there have been few scientifically substantiated recommendations concerning the use of dung-removal robots on perforated flooring. Systematic experiments involving different cleaning frequencies of the Lely Discovery Mobile Barn Cleaner were used to ascertain the height and percentages of floor soiling as well as the behaviour of the cows. An optimised dung-removal frequency showed an improvement vis-à-vis the variants 'without' and 'infrequent' robot cleaning in terms of height of soiling, smear-layer formation, and slipping of the animals. The water-spray function allowed for a significant reduction in the formation of smear layers. Although an interruption in feeding in the case of dung-removal routes right at the feeding barrier, the difference between the feeding cows with and without robot operation was comparatively slight, and the cows generally returned to the feeding place after the disruption.

Keywords
Dung removal, robot, dairy cow, animal behaviour, floor soiling

Dairy loose housing has increased steadily in recent years: around 40% of Swiss dairy cows were kept in loose housings in 2013 (Bundesamt für Landwirtschaft 2016), and in Germany, around three-quarters of dairy cows were already kept in loose housings in 2015 (Deutscher Bauernverband 2015). Besides the advantages in terms of work economics, loose housing systems provide cows more space and opportunity of movement. However, one disadvantage of the greater available space is the soiling of a larger surface area of both solid and perforated flooring with a faeces-urine mixture (FUM). These soiled, and consequently wet, floor surfaces exacerbate claw soiling, thereby increasing the risk of claw diseases (Hulek 2014). In addition, depending on the season and weather, faeces and urine on the flooring can form smear layers, thereby adversely affecting the slip resistance of the animals (Hoy et al. 2016). Furthermore, these fairly large soiled surface areas also lead to higher emissions of ammonia (NH_3) (Zähner 2005). To prevent this, the animals' faeces and urine must be removed frequently from the flooring. This may be done manually, with a hand-held motorised device, a stationary scraper, or a dung-removal robot. The use of dung-removal robots is becoming increasingly common, especially in dairy loose housing with perforated floors. To date, however, so far there are hardly any process-engineering recommendations on the use of these devices, with the result that on many farms the robot's potential cannot be exploited to the full (Strahm 2013). Furthermore, there is a lack of studies on dung-removal robots performed under typical Swiss livestock-housing conditions,

received 27 April | accepted 10 August 2018| published 18 June 2019

i. e. in dairy loose housings with perforated floors combined with deep-bedded cubicles with a straw/dung mattress.

The aim of this study was to evaluate a dung-removal robot in a typical Swiss housing system with perforated flooring and deep-bedded cubicles with a straw/dung mattress in terms of cleaning quality and animal behaviour. For this, the soiling of the floor surfaces was assessed and animal behaviour was observed at different cleaning frequencies as well as with and without the use of the robot's water-spraying function.

Materials and methods

Housing and animals

The experiments were carried out in Agroscope's experimental dairy housing for emission measurements in Tänikon. The experimental dairy housing is conducted as an outdoor climate housing. It has two identical, structurally separated experimental compartments for 20 cows each. Between the two experimental compartments are the milking parlor and waiting area as well as the office, the sanitary area and technical installations. Due to the modular construction and the variable floor elements, different experimental conditions can be realized (Schrade et al. 2015). The studies were conducted with 20 cows in one compartment of the experimental dairy housing for emission measurements (Figure 1). For this, a commercially available concrete slatted floor (Grüter-Handels AG, Buttisholz, Switzerland) with a KURA S rubber covering (Kraiburg, Tittmoning, Germany) was installed in the traffic alleys of the feeding area (feeding aisle) and in those of the lying area (cubicle access area). The solid-floored cross aisles between feeding aisle and cubicle access area were likewise constructed with a KURA P rubber coating (Kraiburg, Tittmoning, Germany) and had a slope of 3% from the centre to the ailses. The feeding aisle and cubicle access area were 330 cm and 260 cm wide, respectively. The triple rows of cubicles consisted of deep-bedded cubicles with a straw/dung mattress, which were topped up with long-stalk straw as standard. The experimental herd consisted of lactating Brown Swiss and Swiss Fleckvieh breeds. The cows (average herd yield during the experiments: 29.6 kg milk per cow and day) were milked twice daily (5:30 am and 4:30 pm) in a steep herringbone milking parlour (2 x 4 milking places). Feed was distributed once daily with a feed mixer at 3.30 pm in the form of a partial mixed ration consisting of grass silage, maize silage, hay, sugar-beet pulp and concentrate, with access to fresh feed after the evening milking only. The average dry matter consumption of the partial mixed ration was 17.4 kg dry matter per cow and day. Individual concentrate distribution took place at a concentrate station.

Dung-removal robot

The Lely Discovery Mobile Barn Cleaner 90 SW (Lely Industries, Maaslouis, The Netherlands) was used for the trials. This is a battery-powered dung-removal robot that cleans perforated floors by scraping the manure and pushing it through the openings in the floor. The device also has a spray function. The Lely Discovery is 136.2 cm long, 57.5 cm high and has a scraper width of 86 cm. It weighs 340 kg, and its sensor ring is at a height of 10.2cm. It can travel at a speed of 10.8 to 18 m/min, and according to the manufacturer can thus achieve a cleaning capacity of 918 m^2/h at maximum speed. The robot needs to charge for around 60% of the time and can therefore run 40% of the time. The Lely Discovery is controlled by a combination of components: A PCB controls the operational sequences of the robot. In addition, each of the two drive motors is equipped with a coder that measures the revolutions of the motor shaft, and calculates from this the distance travelled and the position of the vehicle. An ultrasound sensor measures the distance from the wall, and is an essential precondition of the dung removal robot being able to follow a wall or a grate at a predetermined distance. Furthermore, a gyroscope measures the angle of the curve in order to ensure that the correct direction is followed. The Lely Discovery 90 SW was operated and programmed via Bluetooth with a smartphone control app. The charging station was on the inner wall of the cubicle access area in the immediate vicinity of the water filling station (Figure 1).

Investigated variants

Four different routes were programmed for the studies (Figure 1): Routes 1 and 2 cleaned the same housing areas – the cubicle access area plus the feeding aisle behind the cubicles – with the same route but in the opposite direction. Route 3 cleaned the cross aisles, route 4 the entire feeding area (feeding aisle).

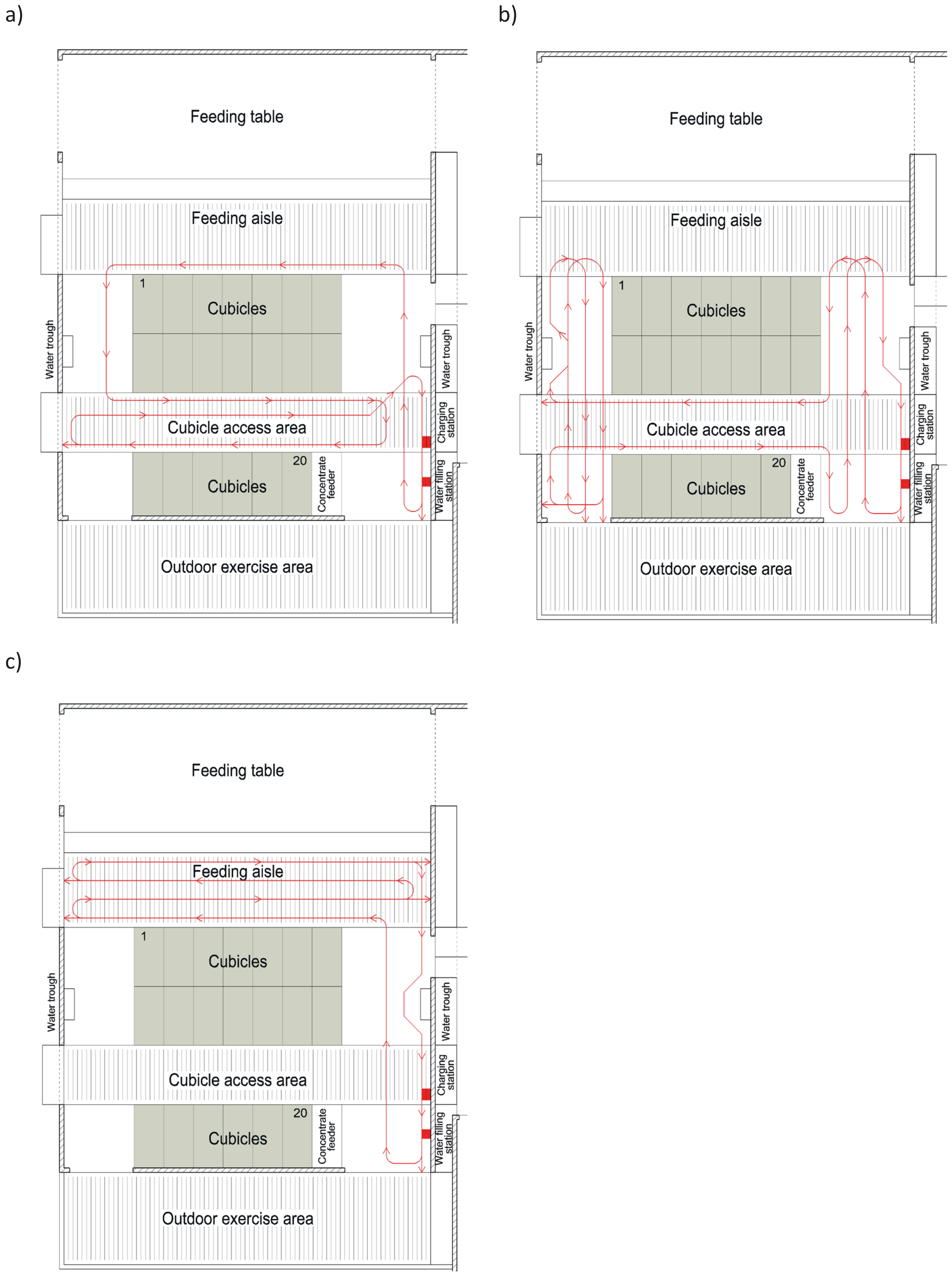

Figure 1: Sketch of the experimental compartment with different cleaning routes: (a) Routes 1 and 2, ‘cubicles’; (b) Route 3, ‘cross aisles’; and (c) Route 4, ‘feeding aisle’

The investigations were carried out in coordination with emission measurements, which took place during the same period. A total of six different variants were determined with regard to the frequency of cleaning and the use of water. These are given in Table 1. In variant 0 there was no cleaning with the robot – just a once-daily scraping of the soiling directly behind the edges of the cubicles, in order to prevent an accumulation of the straw that had spilled out of the cubicles. In variants 1 to 5, different numbers of dung remocal procedures were carried out with the robot; in variants 1, 3, 4 and 5, water was additionally sprayed. Whereas in variants 0 to 4 the cubicles were bedded with long-stalk straw, chopped straw was used in variant 5.

Each variant was studied for four consecutive days under summer conditions (late June to early August 2017). The experiments were preceded by a 20-day adaptation phase to the housing and the robot. If necessary, an adaptation phase and/or an additional cleaning of the floor surfaces took place during the changeover between two variants.

Table 1: Overview of the investigated variants with details on dung-removal frequency according to route

Variant	**0**	**1**	**2**	**3**	**4**	**5**
Dung removal	**none**	**infrequent**	**optimised**	**optimised**	**frequent**	**optimised**
Water	**without**	**with**	**without**	**with**	**with**	**with**
Bedding material	**long-stalk straw**	**long-stalk straw**	**long-stalk straw**	**long-stalk straw**	**long-stalk straw**	**chopped straw**
No. of dung removal events per day	**(n)**	**(n)**	**(n)**	**(n)**	**(n)**	**(n)**
Route 1 (cubicles)	0	4	12	12	18	12
Route 2 (cubicles)	0	4	12	12	18	12
Route 3 (cross aisles)	0	3	5	5	7	5
Route 4 (feeding aisle)	0	1	3	3	5	3

Documentation of areas' soiling

To evaluate the cleaning quality of the dung-removal robot, the soiling on the floor surfaces in the housing was recorded. For this, an assessment scheme based on Korth (2008) and Poteko et al. (2017) was used. In this scheme, the entire area of the barn was divided into a grid of 72 patches and the soiling height of the cubicle access area (CAA), the feeding aisle (FA) and the cross aisles (CA) in that grid were measured at predefined points using a ruler. The percentages of floor soiling were visually estimated according to the different categories of 'faeces, dry', 'faeces, wet', 'urine', 'faeces-urine mixture (FUM), dry', 'FUM, wet', 'straw, wet', 'straw, dry' and 'clean surface', and documented in a 10% gradiation (Poteko et al. 2017). In addition, the proportion of the surface area with a smear layer (manure/urine mixture in which the contact layer with the soil surface is still moist, but the surface of the contamination is dried) was determined in each grid field. The assessment took place daily between 1:45 and 2:25 pm.

Surveying animal behaviour

The behaviour of the cows in connection with the dung-removal robot was recorded in variants 1 to 4 by direct observations on a total of 24 days. Two observers alternated, and the persons were compared several times. Observations were carried out from 7:00 to 8:00 am and from 7:00 to 8:00 pm in each case, as comparatively high animal activity was expected in these periods. The observations took place in blocks of four experimental days each, corresponding to the time periods of the individual variants. The following behaviours were recorded: avoidance (by moving forwards, backwards, with and without contact with the robot, walking past, seeking refuge in the cubicle, drawing hind legs into the cubicle), lying behaviour (getting up and standing still, or getting up and leaving the cubicle) and exploratory behaviour (walking up to the robot, following behind it, sniffing/touching, observing it).

In addition, the following behaviours which involved animals slipping in the different sections of the housing when the robot was paused were documented: walking, displacement by other cows, oestrus behaviour and self-grooming (caudal licking on three legs).

The feeding behaviour of the animals during different robot cleaning frequencies in the feeding aisle was evaluated by means of video recordings (Mobotix M15, MOBOTIX AG, Langmeil, Germany). In all variants, the observation took place daily from 2:10 to 2:30 am, 8:10 to 8:30 am and from 8:10 to 8:30 pm during the robot activity in the feedimg aisle (Route 4). The number of cows at the feeding barrier was noted for every full minute of the observation period.

Recording water and electricity consumption and calculating annual costs

A commercially available water meter (Aquametro, Therwil, Switzerland) which was connected upstream of the water-filling unit and was read for the different variants served to document the water consumption of the spraying device on the dung-removal robot. A commercially available electricity meter (Optec, Wetzikon, Switzerland) was used to record the electricity consumption per variant. An electricity price of CHF 0.16/kWh and a water price of CHF 1.20/m^3 as well as 330 days of use were assumed for electricity consumption and 300 days of use per year for water consumption were assumed in order to calculate the annual costs (Zähner 2017).

Statistical analysis

The statistical software R version 3.3.2 was used for the statistical analysis of the data on areas' soiling and animal behaviour. Since the data were not interval-scaled, parameter-free processes were used for several independent samples. For this, a Kruskal-Wallis H test was used to perform a single-factor analysis of variance in order to determine whether significant differences occurred between the k factor levels (individual variants). In a second step, multiple comparisons were performed with the Wilcoxon-Wilcox-Test (Köhler et al. 2007). A result was rated as significant if there was a p-value of < 0.05.

Results and discussion

Floor soiling

The average soiling height across all areas considered was highest in the 0 and 1 variants, at 5.1 mm and 3.7 mm respectively (Figure 2). The soiling height of the variant without robot cleaning – variant 0 – was significantly higher than for variants 2 to 5 ($p < 0.001$). At 1.6 mm, variant 3 had the lowest average soiling height. Even-more-frequent cleaning as in variant 4 did not contribute to an improvement in cleanliness, as evidenced by that variant's average soiling height of 1.9 mm. At around 1 to 7mm, the overall soiling-height range corresponds to the results of Schrade (2009) on solid floors.

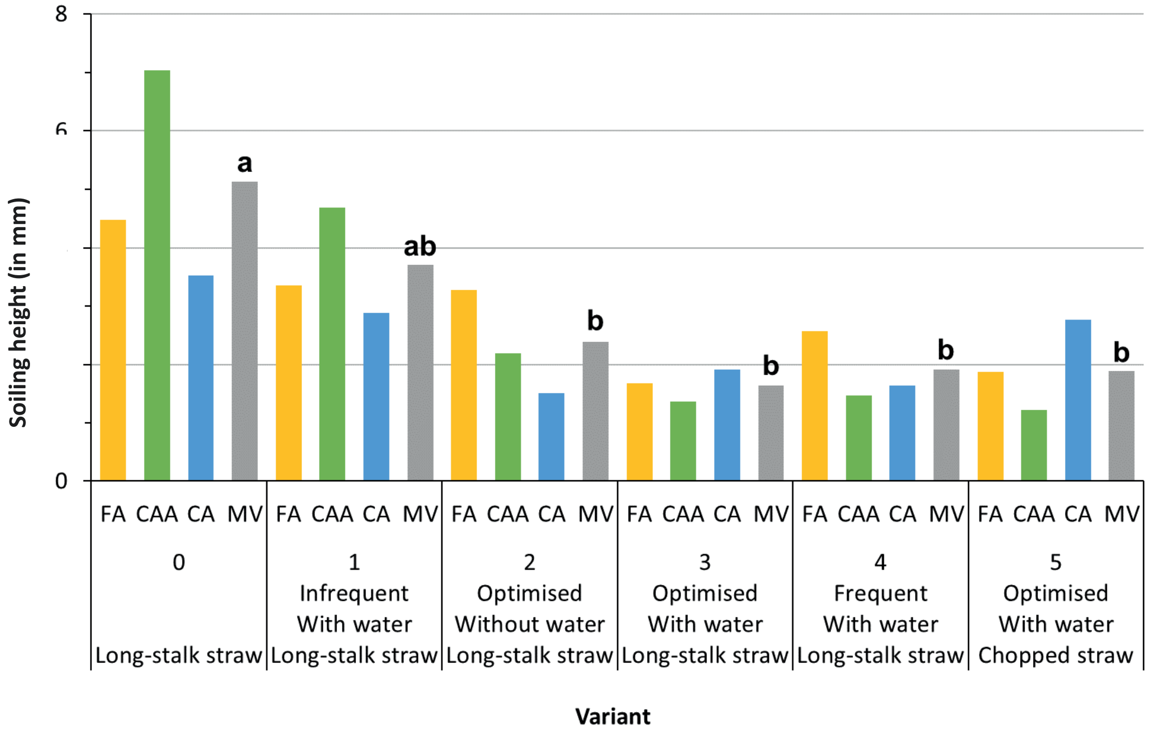

Figure 2: Mean values of the soiling height (in mm) of the six variants differentiated according to feeding aisle (FA), cubicle access area (CAA) and cross aisles (CA), as well as all floors (MV (mean value)). Mean values with the same letter do not differ significantly from one another.

The 'faeces-urine mixture (FUM), dry' and 'FUM, wet' categories accounted for the largest shares of areas' soiling across all variants. The more-frequent cleaning succeeded in reducing the shares of 'faeces, dry' and 'faeces, wet' (Figure 3). Moreover, the area percentages of 'FUM, dry' shifted towards those of 'FUM, wet'. The percentage of 'wet' soiling categories ('faeces, wet'; 'FUM, wet'; 'straw, wet') differs significantly between the variants ($p < 0.001$). The more often the cleaning was accomplished with the use of water, the more often the 'FUM, wet' category occurred, with the percentages of wet soiling being significantly higher in variant 4 than in all other variants. The water sprayed for cleaning could be the reason for this, since as cleaning frequency increased, the surfaces were rewetted more frequently and had less time to dry off. Because the floor was perforated, the presence of urine, which was < 1% for all variants, was significantly lower than the urine percentage of 5 to 12% in experiments with solid floors without a slope (Poteko et al. 2017).

As expected, the 'dry' and 'wet' percentages of straw on the floor when the cubicles were bedded with chopped straw – 4.4% - were significantly lower ($p < 0.05$) than with all other variants. Considering the other variants, it is noticeable that variants 3 and 4 scarcely differ in terms of percentages of straw (6.3% and 6.9%, respectively). A more-intense cleaning by the robot therefore failed to get rid of more straw (Figure 3).

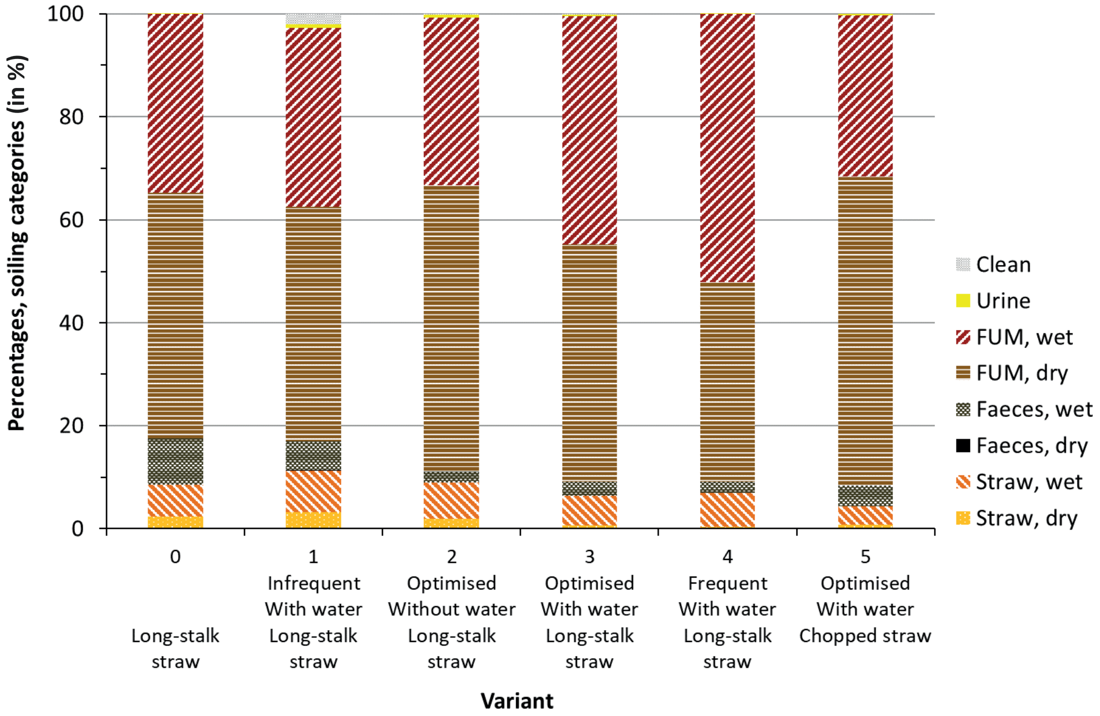

Figure 3: Relative area percentages (in %) of the six variants according to soiling category.

The results for the smear layer reveal increased smear-layer formation in variants 0, 1 and 2 in particular (Figure 4), with the smear-layer percentage of variant 2 differing significantly from that of all other variants ($p < 0.001$). What is striking here is the more frequent formation of smear layers on the solid surfaces of the cross aisles compared to the perforated floors in the both the feeding aisle and cubicle access area. Variants 3, 4 and 5 exhibited significantly less smear-layer formation. Accordingly, frequent manure removal combined with the use of water significantly reduced the formation of smear layers. In places, in all variants, there were soiling residues in the turning areas of the robot and in the area of the water filling and charging station, which also led to the formation of smear layers. These could not be prevented completely, even with frequent cleaning and/or the use of water.

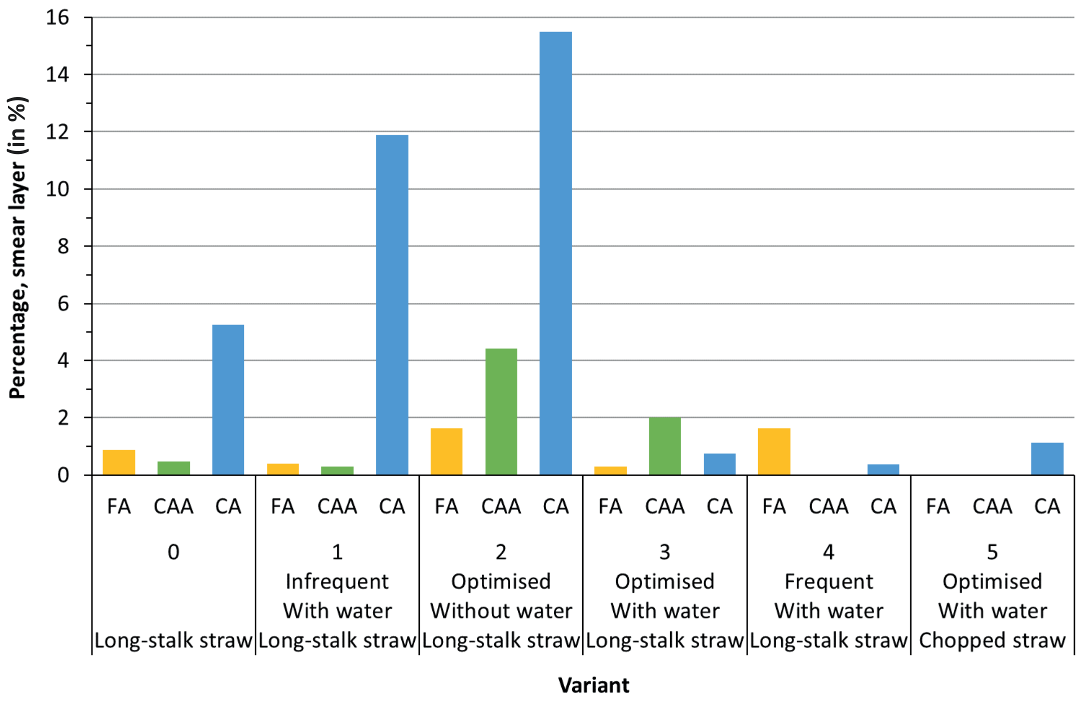

Figure 4: Relative area percentages of smear layers (in %) of the six variants differentiated according to feeding aisle (FA), cubicle access area (CAA) and cross aisles (CA)

Animal behaviour

Experiences and observations in the adaptation phase before the start of the experiment showed that the animals quickly became habituated to the dung-removal robot. Of the 368 behavioural reactions in total to the moving robot during the observation period, 72% could be assigned to the behaviour category ‘avoidance’, followed by ‘exploratory behaviour’ with 16%. Around 11% of the reactions to the robot resulted in the animals leaving the feeding barrier, although in these situations the robot was cleaning the area behind the cubicles at a distance of over a metre. By contrast, a number of animals did not take evasive action until the robot came into direct contact with them, for example running into one of their legs. In the majority of cases, resting animals at most reacted to the robot passing by with attentive ear movements, and only once by standing up. In their paper, Stülpner et al. (2014) mention animals taking refuge in a cubicle while the robot was operating, but did not detect a significantly higher number of animals in cubicles during the dung-removal processes. The present experiment also did not confirm more-frequent visits to the cubicles by the animals. Looking at the different categories of avoidance behaviour, we observed on 14 occasions that a cow already standing with her forelegs in the cubicle also pulled in her hind legs when the robot approached. At no time during the observation period did a cow enter a cubicle completely from the aisle in order to avoid the dung-removal robot (Figure 5). One explanation for this could be that the animals in the experimental housing had enough space to avoid the robot in the aisles, and therefore did not need to use the cubicles as an avoidance area. This could also be an advantage of the mobile dung-removal robots, which are significantly narrower than a stationary scraper.

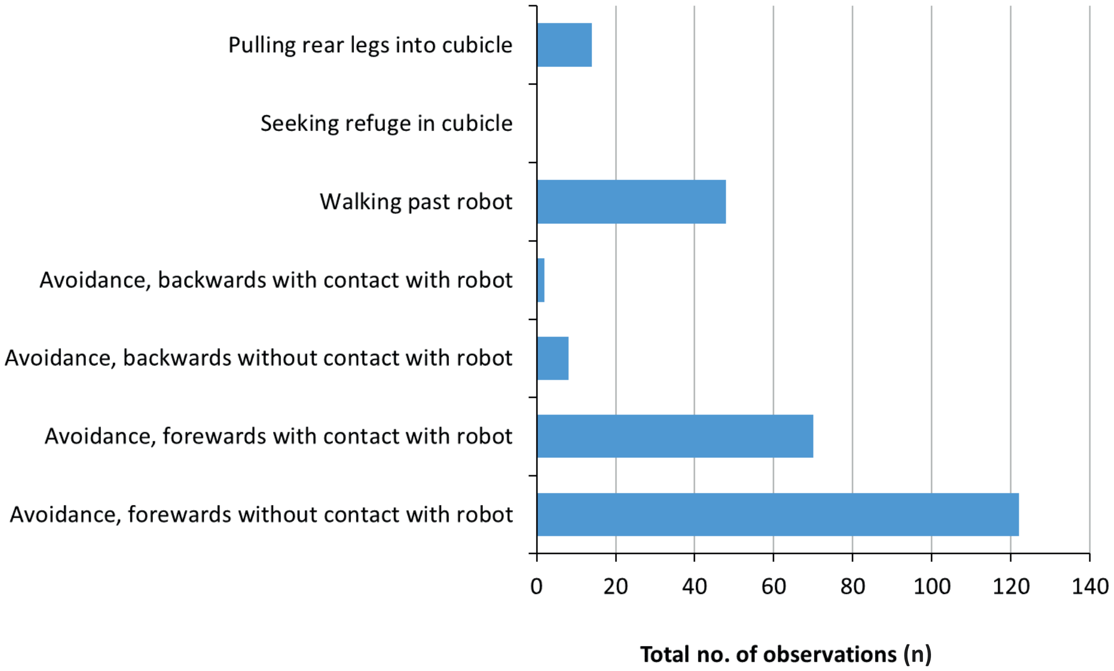

Figure 5: Avoidance behaviour differentiated according to different behaviours, expressed as the total number of observations (n) during the observation period across variants 1 to 4

The comparatively high number of events involving ‘avoidance through forward movement without contact’ and ‘walking past the robot’ (122 and 48 events, respectively) noted during the observation period confirms that, after an adaptation period, the animals have learned to gauge the robot’s behaviour, and avoided it as a precautionary measure. With the experimental approach used here, we did not detect any stress on the part of the cows during these avoidance reactions. In this context Doerfler et al. (2016) took heart-rate measurements to measure stress, but the only conclusion reached by them was that whilst the cardiac activity of the test animals rose during robot operation, it moderated with increasing distance to the device. This only applied for non-resting animals, however: In Buck et al.’s (2012) experiments with stationary scrapers, a slight stress on the part of the animals during the scrapinng process could only be detected for the behaviours ‘lying’, ‘standing in the aisle’, and ‘standing in the cubicle’. This did not apply for ‘direct confrontation’ behaviours, such as e. g. stepping over the scraper.

Reactions assigned to the category “exploratory behaviour” in these experiments tended to decrease over the course of the studies. In the final variant, a decrease in interest was observed despite more-frequent robot activity, and hence despite the more-frequent presence of the moving robot. This also points to the animals becoming habituated to the robots, which confirms Doerfler et al.’s (2016) presumption of habituation. This decrease in interest was observed despite more-frequent robot circulation in the final variant, and hence despite the more-frequent presence of the moving robot in the housing.

The most common situation in which cows slipped regardless of the operating robot was ‘walking’ (83 events), followed by ‘displacement by another cow’, with 68 events. During the observation period, however, 127 mutual displacement events were documented in which no slipping occurred. Slipping during ‘self-grooming’ (caudal licking on three legs) occurred on only 10 occasions. By contrast, there were 172 self-grooming events with no slipping.

The results showed that different floor-cleaning frequencies were associated with higher or lower slip resistance on the part of the animals. Differences between the variants were not significant (p = 0.08). The majority of slipping events were observed in variants 1, 3 and 0, and were about 40 in number in all three cases during the observation period. Cows slipped significantly less in variants 2 and 4 (Figure 6). Only half as many slipping events (20) occurred in the latter as, for example, in variant 3. The reason for these results could lie in the weather conditions during the trials. The weather was not the same throughout the experimental days; in addition to very hot days, there were days with heavy rainfall. Especially hot, dry weather can lead to dried soiling, which makes it harder for the robot to push the manure through the floor perforations (House 2012).

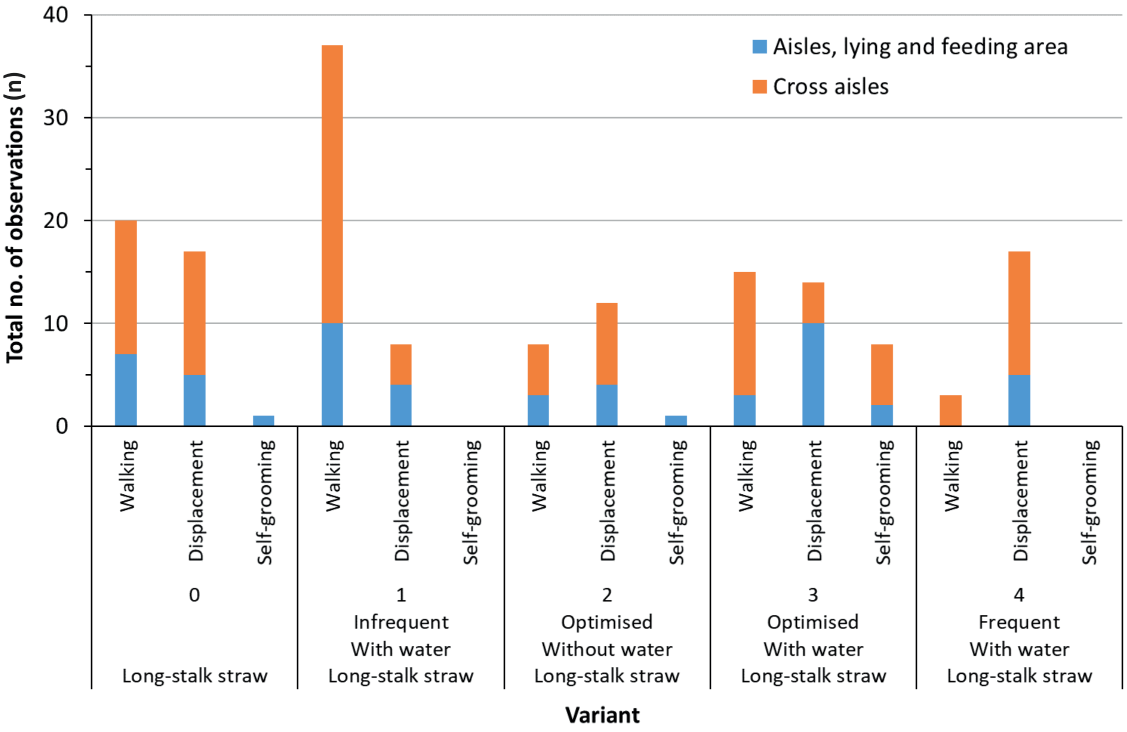

Figure 6: Slipping events according to behaviour and variants, given as the total number of observations (n) in the respective observation period differentiated according to aisles in the lying and feeding areas or cross aisles

The number of slipping events on the cross aisles was, however, significantly higher than in the aisles in the lying and feeding areas (p = 0.001). One reason for this could be the increasingly frequent occurrence of smear layers on the solid floors of the cross aisles.

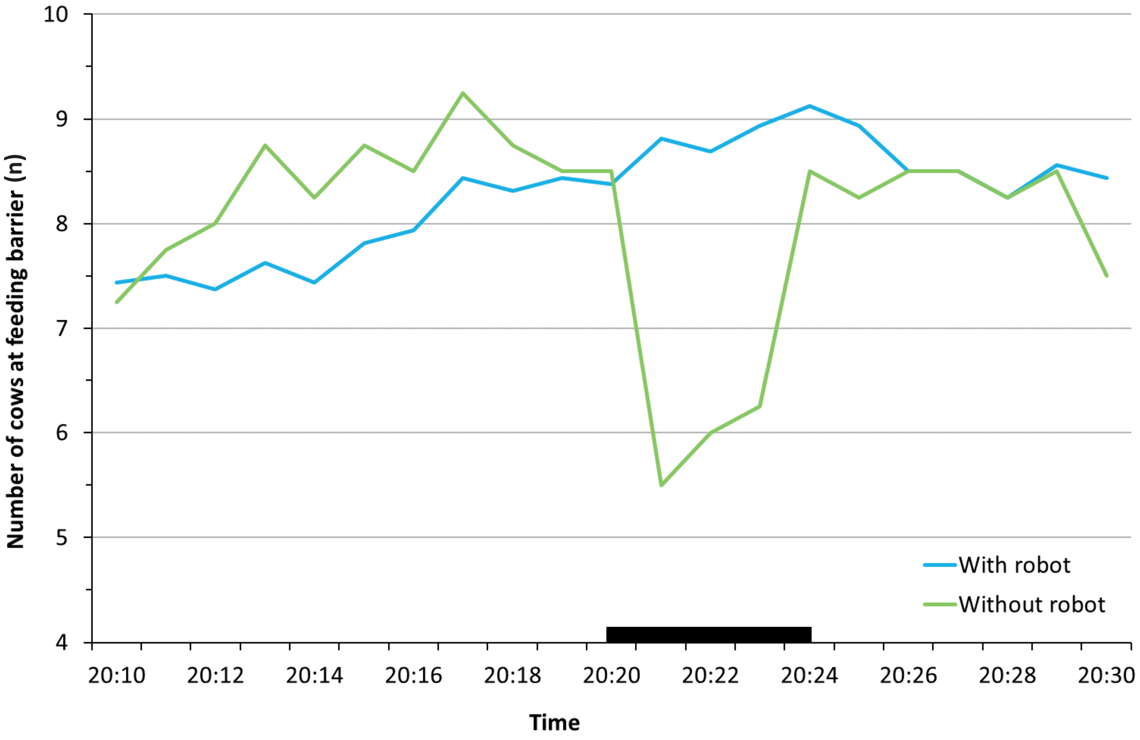

Fig. 7: Number of cows at the feeding barrier (n) in averages of the variants with robot (variant 4) and without robot (variants 0 to 3). Between 20:19 and 20:23 the robot was running in the cows' area near the feeding barrier (black bar).

During observation of the animals at the feeding barrier between 8.10 and 8.30 pm, a marked effect of the robot was in evidence from 8:21 to 8:24 pm (Figure 7). From 8:20 to 8:21 pm, the number of feeding cows for the variant "with robot" fell from 8.5 to 5.5 animals per minute (averages) while the robot drove directly behind the feeding barrier. The number of cows at the feeding barrier at 8.30 pm while the robot was cleaning – 8.0 animals per minute – was comparable to the average of the variant "without robot", 8.3 animals per minute. Although the animals had to take evasive action with the dung-removal robot, they returned afterwards to the feeding barrier.

A dung-removal robot is not the only device that potentially disturbs feeding animals when the feeding area is being cleaned. A stationary scraper in the feeding aisle also causes the animals to interrupt their feeding, either to walk away from the device or step over it (Buck et al. 2012). Here, the comparatively small dimensions of the robot are actually an advantage; since the robot does not clean the entire aisle at once, the cows have more space and avoidance options. Observations have shown that in the vast majority of cases, feeding cows returned soon afterwards to the feeding barrier, and even if they were driven away by the robot several times, only interrupted their feeding activity for as long as was absolutely necessary.

Water and electricity consumption, annual costs

Increased water costs and more water in the slurry store are often given as reasons why the dung-removal robot's water-spraying function is not used in agricultural practice. Water consumption per cow and year ranges between 1.3 m³ and 4.9 m³ for the different robot variants with the spraying function (Table 2). By way of comparison, the water consumption of an automatic milking system stands at around 6.1 m³ per cow and year (Landesamt für Umwelt, Landwirtschaft und Geologie Sachsen 2013).

With a water volume of around 3.2 m³ per cow and year, the water costs for variant 3 come to around CHF 3.8 per cow and year. Variant 3's electricity costs come to CHF 3.7 per cow and year.

Table 2: Water and electricity consumption per cow and year, as well as annual costs in CHF of the six variants.

Variant	**0**	**1**	**2**	**3**	**4**	**5**
Dung removal	**none**	**infrequent**	**optimised**	**optimised**	**frequent**	**optimised**
Water use	**without**	**with**	**without**	**with**	**with**	**with**
Bedding material	**long-stalk straw**	**long-stalk straw**	**long-stalk straw**	**long-stalk straw**	**long-stalk straw**	**chopped straw**
Mean annual water consumption (in m³)	0	1.3	0	3.2	4.9	3.2
Annual water costs (in CHF)	0	1.5	0	3.8	5.8	3.9
Mean annual electricity consumption (in kWh)	0	13.2	19.8	23.1	31.4	22.3
Annual electricity costs (in CHF)	0	2.1	3.2	3.7	5.2	3.6

Conclusions and recommendations

The systematic studies of the various cleaning frequencies under summer conditions showed an additional cleaning of the perforated flooring using a stationary scraper or dung-removal robot to be imperative, in view of the soiling height and slipping resistance. Pushing the soiling through the perforation by the animals alone (variant 1) is not sufficient. The results suggest that, compared to variant 4 with frequent dung-removal frequency and water use, variant 3 with optimised dung-removal frequency and water use did not bring about any substantial improvement in floor cleanliness. The use of the robot's water-spraying function improved the cleanliness of the floor surfaces. Most notably, it also reduced the smear layers, and consequently the slipping of the animals. Accordingly, continued use of the water is the most sensible course of action. Since the water costs cannot be regarded as negligible, the robots could be programmed to use the water spray on every second dung-removal round, by way of compromise.

Even with frequent dung removal, the robot was unable to push the long-stalk straw used as cubicle bedding during the experiment through the perforations in the floor. Using chopped straw as bedding material significantly reduced the proportion of straw remaining on the floor surfaces. Consequently, no long-fibred bedding material such as long-stalk straw should be used where a dung-removal robot is used to clean perforated floors.

The observed reactions of the animals both in the adaptation phase and during the experiments suggest that the animals quickly get used to the device.

Another possibility is for the feeding aisle to be cleaned several times a day. To keep disturbance of the feeding animals to a minimum, we recommend cleaning the area around the feeding barrier whilst the cows are in the waiting area or are being milked, or alternatively outside of the main feeding periods.

References

Buck, M.; Wechsler, B.; Gygax, L.; Steiner, B.; Steiner, A.; Friedli, K. (2012): Wie reagieren Kühe auf den Entmistungsschieber? Untersuchungen zum Verhalten und zur Herzaktivität. ART-Bericht 750, Agroscope Reckenholz-Tänikon Research Station ART, pp. 1–8

Bundesamt für Landwirtschaft (2016): Agrarbericht 2015. Bern

Deutscher Bauernverband e.V. (2015): Faktencheck „Haltung von Milchkühen“. Deutscher Bauernverband e.V. (DBV), Berlin

Doerfler, R. L.; Post, K.; Winckler, C.; Bernhardt, H. (2016): Räumlich-zeitliches Verhalten und Herzaktivität von Milchkühen bei der Einführung eines Spaltenroboters. In: Aktuelle Arbeiten zur artgemäßen Tierhaltung 2016. 48. Internationalen Arbeitstagung Angewandte Ethologie bei Nutztieren der Deutschen Veterinärmedizinischen Gesellschaft e.V. (DVG) Fachgruppe Ethologie und Tierhaltung. KTBL-Schrift 511, Darmstadt, pp. 178–186

House, H. K. (2012): The Use of Robotic Slat Cleaners to Clean Slatted Floor Dairy Barns. Ontario Ministry of Agriculture Food and Rural Affairs (OMAFRA) Clinton, Ontario

Hoy, S.; Gauly, M.; Krieter, J. (2016): Nutztierhaltung und -hygiene. Verlag Eugen Ulmer UTB, Stuttgart

Hulek, M. (2014): Klauengesundheit & Klauenpflege. Leopold Stocker Verlag, Graz

Köhler, W.; Schachtel, G.; Voleske, P. (2007): Biostatistik – Eine Einführung für Biologen und Agrarwissenschaftler. Springer Verlag, Berlin Heidelberg

Korth, F. (2008): Tieraufenthalt und Verschmutzung im Stallbereich und auf dem Laufhof in der Milchviehhaltung. B.Sc. Thesis, Faculty of Agricultural and Nutritional Sciences, Kiel and Agroscope Reckenholz-Tänikon Research Station ART, Tänikon

Landesamt für Umwelt, Landwirtschaft und Geologie Sachsen (2013): Automatische Melksysteme in Sachsen. Nutzung Automatischer Melksysteme (AMS) in der sächsischen Milchproduktion. Unter Mitarbeit von René Pommer, Steffen Pache, Ingo Heber und Anett Rindfleisch. Landesamt für Umwelt, Landwirtschaft und Geologie Sachsen

Poteko, J.; Zähner, M.; Kreuzer, M.; Schrade, S. (2017): Laufflächen-Verschmutzung – Erhebungskonzept und erste vergleichende Ergebnisse von planbefestigten Laufflächen mit und ohne Gefälle aus dem Emissionsversuchsstall für Milchvieh. ETH Schriftenreihe zur Tierernährung 40, pp. 110-113

Schrade, S. (2009): Ammoniak- und PM10-Emissionen im Laufstall für Milchvieh mit freier Lüftung und Laufhof anhand einer Tracer-Ratio-Methode. Dissertation. Christian Albrechts University Kiel, Institute for Agricultural Process Engineering, Kiel

Schrade, S.; Zähner, M.; Poteko, J.; Steiner, B.; Keck, M.; Sax, M.; Herzog, D.; Schick M. (2015): Versuchsstall zur Entwicklung und Quantifizierung von Maßnahmen zur Minderung von Emissionen. In: Bau, Technik und Umwelt in der landwirtschaftlichen Nutztierhaltung, KTBL, Darmstadt, pp. 450-455

Strahm S. (2013): Steuerung und Betrieb von Entmistungsanlagen und –robotern im Tierbereich. Bachelorarbeit, ETH Zurich, Zurich

Stülpner, A.; Adeili, S.; Haidn, B.; Dörfler, R.; Bernhardt, H. (2014): Reaktionen von Milchkühen beim Einsatz eines Spaltenroboters. Landtechnik 69(5), pp. 225–231

Zähner, M. (2005): Vorsorgliche Emissionsminderungsmaßnahmen bei Bauinvestitionen in der Landwirtschaft. Schlussbericht. Agroscope FAT Tänikon, Swiss Federal Research Station for Agricultural Economics and Engineering, Tänikon

Zähner, M. (2017): Strom- und Wasserpreise Schweiz. Personal Communication, Tänikon

Authors

Theresa Leinweber, M.Sc. was a master’s student at the University of Hohenheim and wrote her master’s thesis at the Institute of Agricultural Engineering, Garbenstraße 9, 70599 Stuttgart in collaboration with Agroscope in Tänikon.
Dr. sc. nat. ETH Michael Zähner and **Dr. sc. agr. Sabine Schrade** are research scientists at Agroscope, Tänikon 1, 8356 Ettenhausen, Switzerland, email: michael.zaehner@agroscope.admin.ch

Acknowledgements

We would like to thank the technicians and Agroscope’s workshop at the Tänikon site for their technical support. Our thanks also go to the Tänikon experimental farm staff (BBZ Arenenberg, canton of Thurgau) for their excellent teamwork.