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Dairy barns, robots and queueing networks

by Ivo Adan and Jan van der Wal

Robotic milking is the most important recent development in the dairy industry. By using robots, cows can be milked more frequently, so their production may increase by about 15 percent. Milking robots, however, are very expensive. That is why it is important to develop models, which make it possible to discuss the optimal layout of a robotic milking barn (RMB) and the optimal capacities of the various facilities in the barn depending on the herd size before actually constructing it.

In an experimental farm in Duiven in the Netherlands the agricultural research center IMAG-DLO is investigating the behaviour of the cows in an RMB. Based on extensive measurements and observations, it was in [2] concluded that it is necessary to incorporate the stochastic behaviour of the cows in the design of an RMB. Another aspect, which makes this design complex, is the interaction between the facilities in the barn: increasing the capacity of bottleneck facilities will shift queues and alter the location of bottlenecks, possibly forcing the designer to increase the capacity elsewhere. The concept of the closed queueing network (CQN) seems to be very appropriate for modelling and analysing an RMB. It covers both the random behaviour of the cows and the interaction between the queues. It also supports a systematic analysis of the tradeoffs between economic and cow-social factors. The CQN model is widely used in the communication systems and production systems areas. The present application area, the design of RMBs, is new.

Based on the CQN the Java applet *Cow* has been developed, which allows the user to easily and efficiently evaluate and compare alternative designs. We will first describe the milking robot and the dairy barn in more detail. Then we introduce our queueing network model of the barn. Finally we discuss the Java applet and show that this tool is very useful for the design of a barn.

The milking robot

The milking robot is shown in figure 1. Milking robots are different from the ordinary milking machines in one crucial aspect: the robot uses sensors to find the teats of the cow and then connects the cups to the teats with a robot arm. Milking robots, their operation and costs have been extensively reviewed in e.g. [1, 6, 7].

So milking is done without intervention of the farmer. This saves the farmer serious amount of labour. Further, it makes it possible to go from milking twice a day to three or even more times a day. When cows are milked three times a day their production is increased by about 15 percent.

Figure 1: A milking robot.

The barn

The basic layout of the RMB we are dealing with is shown in figure 2. In the barn we distinguish six facilities or servers.

Figure 2: Layout of the experimental barn in Duiven. Dimensions in mm. (source: IMAG-DLO).

- (1) The *Milking Robot* described above.
- (2) The *Concentrate Feeder*. This is a computer-controlled feeder with 'concentrate' food. Each cow is allowed to receive only a limited amount of concentrate, cf. [4]. So the Concentrate feeder must have the equipment to be able to identify the cows and to decide how much concentrate to give to the cow. Cows are very fond of the concentrate. Therefore the Concentrate feeder can be and is used to lure the cows into the Milking robot. In the present design in Duiven the cows can only reach the Concentrate feeder by passing through the robot.

The other three more conventional facilities are:

(3) The *Forage Lane*. This is a row of forage troughs with the 'usual cow menu.' There are no limitations on foraging. The only condition is that there must be enough eating positions at the forage feeder to prevent the cows from becoming aggressive.

(4) The *Water Troughs* or drinking places. Water troughs are cheap, but of significant physiological importance, because a 'high-yielding' cow should drink a lot (up to 180 liter) to be able to produce 30 up to 60 liter milk per day.

(5) The *Cubicles*. In the cubicles the cows can lay down, rest, and avoid confrontations. They spend roughly 50 percent of their time in the cubicles. Cubicles only require space, some fencing and bedding material (wood shavings, sand, rubber mattresses).

Further we need one more, artificial, facility:

(6) *Walking*. The space in between the facilities is used for walking, idling or grouping. This takes nearly 25 percent of their time, so 5 to 6 hours a day. In that time they cover at most a few kilometres, so a better word for the facility might be 'Standing' or 'Hanging.' Anyway, the walking area should be large enough to accommodate somewhat more than 25 percent of the herd.

The queueing network model

The cows use the above mentioned six facilities in the barn. Their capacities are limited, so it may happen that cows have to wait, something they don't like. In this respect they don't differ from humans.

Both service times and visiting order of facilities are stochastic (see [2]). This suggests that the barn can be modeled as a closed queueing network with the following six stations: (1) Milking Robot, (2) Concentrate Feeder, (3) Forage Lane, (4) Water Trough, (5) Cubicles, and (6) Walking.

In this queueing model the customers are, of course, the cows. The model is 'closed' because the population of customers (the herd) is constant. Every station has multiple servers. Except for Walking. This can be modeled as a station with 'infinitely many' or 'ample' servers, because in this station a cow never has to wait for service. The queueing model is schematically shown in figure 3.

Figure 3: Closed queueing network model of the barn

The service times for each station and visit frequencies to the stations have been obtained from measurements in the experimental barn in Duiven [2]. This data is listed in table 1. The visit frequency of a station is the mean number of visits of a cow to this station in between two successive visits to Walking (a cycle in figure 3). From the measurements in Duiven we know that a cow spends 25 percent of her time on walking.

	mean	st. dev.	frequency
Milking Robot	8.4	2.5	0.16
Concentrate Feeder	6.4	6.2	0.15
Forage Lane	15	12	0.24
Water Trough	3.2	2.3	0.17
Cubicles	39	60	0.28

Table 1: Service times and visit frequencies

Waiting is important. In queueing networks we are normally interested in the mean waiting times and the mean numbers of 'customers' or 'jobs' at the various stations. In our case this is not different. Particularly at the scarce facilities Milking robot and Concentrate waiting has to be limited. When a cow is waiting and another cow arrives, aggressive behaviour might occur. So the discussion about the design focuses on mean waiting times and mean queue lengths at the stations Milking robot and Concentrate feeder and on the maximum number of cows that can be accommodated in a certain design without having problems with aggressive behaviour.

Given the visit frequencies, service times, capacities and herd size we can evaluate waiting times, queue lengths and utilizations for the various facilities by means of an (approximate) *mean value algorithm*. This is an efficient calculation scheme based on relations between throughput, mean waiting time and mean number of cows in each station (see [5, 3]).

The Java applet

The mean value algorithm has been implemented in a user-friendly Java applet called *Cow*. The performance of the barn can be easily and efficiently evaluated with the applet. It offers several possibilities to show the results, i.e. in the form of bar charts, pie charts or simple text charts. The applet *Cow* can be used freely on the World Wide Web. The URL is:

<http://www.win.tue.nl/cow/cow.html>

This applet has been developed by Marko Boon and Michel Vollebregt, (former) Mathematics students at the Eindhoven University of Technology.

Figure 4: Output screen Cow for the start configuration.

Usage of Cow proceeds as follows. Suppose, a farmer wants to determine the capacity in each facility required for his herd. The starting point is the barn described in the previous sections with the following capacities. There are 2 milking robots, 1 concentrate feeder, 12 forage troughs, 3 water troughs and 27 cubicles. The herd consists of 60 cows. To determine the required capacity we use the criterion, stating that the mean waiting time in each facility may not exceed 4 minutes.

Figure 5: Occupation rates of the facilities for the start configuration.

In figure 4 we see the output of Cow. The layout of the barn corresponds to the one shown in figure 2. In each facility we see a number of 'cow faces'; the smiling, cute

(light) faces correspond to cows in service, the angry (dark) faces to cows waiting for service. The walking cows (in between the facilities) are displayed as small cows. The number of cows corresponding to exactly one face or small walking cow is shown at the bottom of the screen (in this case, five cows).

Figure 4 shows that there are too many cows waiting for the concentrate feeder. Apart from mean number of cows in each station, it is also possible to look at other performance characteristics. In figure 5 we display occupation rates. Here we also see that the feeder is too heavily loaded.

The long queue at the concentrate feeder can be reduced by adding an extra feeder. Then, possibly, the bottleneck shifts to another facility, which also needs extra capacity, and so on. Using this heuristic procedure we find a suitable design of the barn. The result is a barn with 4 milking robots, 4 concentrate feeders, 12 forage troughs, 3 water troughs and 30 cubicles. The mean waiting times are displayed in figure 6. In each facility the mean waiting time is below 4 minutes.

	Service time	Waiting time	Total
Concentrate	6.4	0.9	7.3
Forage	15.0	0.6	15.6
Water	3.2	0.2	3.4
Cubicles	39.0	3.2	42.2
Milking	8.4	2.8	11.2

Figure 6: Mean waiting time for the final configuration.

It is also possible to compare different designs in a single screen. In figure 7 we see results for the start and final configuration. Clearly, in the final configuration, cows are spread out more evenly over the stations.

It is striking that many expensive robots are needed to keep the waiting times small. The reason is inefficient use of the robots. In the present layout the mean total number of visits to the robots per day (the throughput) is 560. So each cow visits the robot nearly 10 times per day. But a cow is milked only 3 or 4 times a day. Hence, the other 7 times, the cow occupies the robot, not because she has to be milked, but because she wants her candy (concentrate). Unsuccessful visits to the robot may be avoided by means of a selective *gate* in front of the robot, through which only cows may pass who have to be milked.

Figure 7: Mean number of cows in the various stations for the start and final configuration.

The effect of a selective gate on the required milking capacity can be evaluated with Cow. It is not completely clear how this will alter the service times of the robot, but let us assume that the service time of a successful visit to the robot has the same mean and standard deviation as in table 1. We only have to reduce the visit frequencies to the Robot and the Concentrate feeder (since it can be reached only by passing through the Robot, see figure 2) with approximately 60 percent to 0.05 (see table 1). The result is a substantial cost saving: for a herd of 60 cows we now need 2 instead of 4 robots, and 2 instead of 4 feeders. On the other hand, two extra cubicles are required to keep the waiting time for the cubicles below 4 minutes, but they are not expensive. In figure 7 this configuration is compared with the other ones.

Conclusion

In this paper we presented a closed queueing network model for a robotic barn. Based on this model we developed a practical tool to support the design of these expensive barns. Queueing network techniques are still uncommon in the analysis and design of livestock housing. As we demonstrated in the present study, these techniques appear to be very useful for design problems in this area as well.

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