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*Review*

# Design of Free Stalls for Dairy Herds: A Review †

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**Abstract:** Lying is an important behavior of dairy cattle. Cows should spend more than 50% of a day lying as it has a high impact on their milk yield and animal welfare. The design, size, and flooring properties of the free stalls influence the time cows spend lying, the way they lie down, and their rising movements. The purpose of this review is to provide an overview of the currently available information with the aim to assist farmers and advisors to come to an optimal design of the free stalls. The design of the free stalls should enable the cows to move and lie in positions as natural as possible. Cows should rest, with all parts of the body, on a clean, dry and soft bed, be able to stretch their front legs forward, lie on their sides with unobstructed space for their neck and head, and rest with their heads against their flanks without hindrance from a partition. When they stand, they should not be hindered by neck rails, partitions, or supports. A comfortable place for cows to lie down helps cows to stay healthy, improve welfare, and increase milk yield. Hence, the probability of a longer productive life for the cows increases and the number of replacements per year decreases.

**Keywords:** dairy cattle; cow comfort; lying time; animal welfare; bedding



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## 1. Introduction

Under natural conditions, cattle are gregarious animals searching for food, water, safety, and comfortable resting places [1,2]. Due to domestication, man has taken the responsibility to care for them as well as supply them with proper housing. This review focuses on the design of a free stall as a place to rest for cows. Lying is an important behavior of dairy cattle and adequate rest is essential to maintain the health, welfare, and productivity of dairy cows, factors all influenced by stall design. Hence, stall design is of major importance for animal welfare and behavior [2–7].

In countries where pasture-based semi-natural systems are common (e.g., Uruguay), many cows have productive lives of over 10 years [8]. In intensive barn-based systems, however, this is an exception [9–13]. This may indicate that the conditions on a commercial farm may not be ideal for all dairy cows. Several reasons for culling, like mastitis and lameness [14–17], are free stall related. On one hand, farmers want to ensure that their cows are well cared for, but on the other hand, they are faced with economic challenges. An increase in the average age of the herd is normally economically beneficial, because replacement cows cost a substantial amount of money and labor, and somewhat older cows, if healthy, produce more milk per year [15,18]. Therefore, proper housing conditions are crucial for the economic results of a farm [19]. One should also keep in mind that alternatives to the free stall exist. For example, cows prefer an open pack area in comparison with comfortable free stalls [20,21]. Compared to straw yard or open pack area housing, the main difference is that the lying area in a free stall housing system is divided into individually protected places for lying that also implies an intended orientation of the

cow when resting. The restrictions of the free stall are used mainly to control defecation behavior [22] as well as save space, labor, and bedding material [23]. Several studies on different aspects of the free stall design are reviewed in the present paper to assist farmers and advisors to come to an optimal design of the free stalls. Ultimately, this should help to improve animal welfare, increase the productive live, and optimize lifetime milk yield. The rest of this paper is organized as follows. A brief history is presented in Section 2, followed by general aspects of a free stall barn that have to be considered when designing dairy barns with free stalls. Section 3 discusses the importance of lying for cows, and Section 4 the number of cows per stall. Then, the components of the free stall are described in Section 5. The free stall components may conflict with the cow body, her movements, etc., hence proper design/location is of importance for animal welfare. Furthermore, other considerations of free stall design are discussed in Section 6 like cow comfort, economic aspects, and future perspectives. To conclude, the optimal free stall is described in Section 7.

## 2. History of the Free Stall System

The free stall system seems to have been invented in the late 1950s by Major Bramley in the UK [23]. His idea was to make use of plastic foam mattresses as bedding instead of straw in pens, mainly to reduce the need for bedding material. However, he soon realized that the animals had to be restricted in some way to limit the contamination of their resting place. The solution was the first free stall with the basic idea to control the defecation behavior of the cows [23–25]. For optimal function, the free stall design has to be designed according to "animal demands", as very well pinpointed by Major Bramley himself in 1962: *"The size of the cubicle must be adequate to enable the animal to stand and lie down in comfort but at the same time its positioning must be reasonable accurate, and the permissible margin of movement restricted so that it cannot stand forward or move sideways sufficiently to enable it to dung and urinate on the bedding"* [23]. It is interesting that the inventor of the system from the very beginning already used soft mattresses and focused on stall size versus space needed for performing natural behavior and movements.

Expanding farmers appreciated the system due to saving straw material [26] and work load, and it soon became widespread in large herds in the USA and Europe and is now widely used around the world for all herd sizes. In the beginning, free stalls were usually home-made, based on the farmers' own ideas [26]. The first free stalls were made of wooden planks and separated the cows completely from each other. Very soon, the dividers were made of metal tubing with a more open design [25]. The major developments since this time are the introduction of open cantilever stall dividers, number and position of rails, and brisket locators as well as several types of more or less soft free stall bases.

## 3. Lying Behavior

In a comfortable environment, cows lie for 12–16 h and rise 9–14 times per day, although there are individual and seasonal variations [2,3,25,27–29]. It is not an aim per se to maximize lying time to more than 12–13 h per day [2], as prolonged lying can also be an indicator of disease. Lying is important for the welfare of cows and has a high priority when compared to feeding and drinking [2,4–6]. Because increases in the concentration of cortisol are commonly associated with stress and a lower level of welfare, it is interesting to see that a stress response was evident in the concentration of cortisol in cows deprived of lying relative to the control cows with an unrestricted possibility to lie down [4]. Additionally, the reaction of cortisol to an acute stressor or ACTH injection increased [4,30]. Furthermore, the concentration of growth hormone was lower after deprivation of lying [31]. Behavioral activity is used as an indication of animal comfort, and lying and standing behaviors are often used as a sign of well-being in cattle and to evaluate the quality of stalls [2,32] or different housing environments [7,33]. One should, however, remember that lying time is also influenced by parameters other than stall design. One example is that cows on pasture have shorter lying times because they need to graze, and this costs more time than eating

at a feed bunk [7]. Higher yielding cows also have shorter lying times because they need to spend more time eating [33]. One should, therefore, not compare lying times strictly in order to define better welfare, but when comparing within a certain husbandry system, and taking certain cow specific characteristics like milk yield into consideration, lying time is an attractive indicator for welfare that could be measured automatically with a sensor [34]. Lying may be considered a sign of positive welfare, while standing is usually more a sign of negative welfare, and activity in general has no clear association with welfare, since increased activity may be more indicative of stress and pain, while decreased activity may be a sign of illness [34].

## 4. Number of Cows Per Stall

Cows need to have access to a clean and attractive resting place at all times. This implies that there should be at least an equal number of free stalls and cows in the barn [35], which is a common recommendation [36,37], and even mandatory in some countries (Austria, Norway, Sweden, etc.). Cows synchronize their behavior and eat, ruminate, and rest at the same moments. This is emphasized on farms with conventional milking parlors, where cows wait, are milked, and then fed afterward [7]. Robotic milking might alter the synchronized behavior slightly. Overstocking, already with one percent more than one cow per stall, leads to shorter lying times and more time spent standing idle in alleys [38–41]. Although the cow:stall ratio often has an effect in experimental studies, it rarely shows up as a significant factor in epidemiological studies. Overstocking leads to more competition between cows for a place to lie down [40,41]. Overstocking at levels of >115–120% may also lead to claw lesions, another factor reducing milk yield and animal welfare [6,42–45]. However, there seems to be little focus on changes in group behavior when resting time increases/decreases in the scientific literature.

## 5. The Free Stall

A free stall should be designed to provide the animals with a suitable, safe, and hygienic resting place, allowing normal behavior (e.g., normal lying down and raising movements), however, at the same time, defecation behaviors should be controlled. The design of the free stalls should enable the cows to move and lie in positions as natural as possible. Cows should be able to rest, with all parts of their body, on a clean, dry, and soft bed; be able to stretch their front legs forward; lie on their sides with unobstructed space for their neck and head; and rest with their heads against their flanks without hindrance from a partition. When they stand, they should not be hindered by neck rails, partitions, or supports [46]. Hence, when using a stall construction with several fixed restrictions, there is a risk that normal behavior during rest, lying down, and rising may be influenced or restricted too much [47]. Some design and management parameters may also have other effects than intended or even negative effects on other traits [48]. One example may be that larger stalls are positive for the lying time of the animals [49] but are also associated with more dirt in the stalls [22,50]. Consequences of design errors may be related to health, production, behavior, or hygiene. Dirty stalls and cows are associated with an increased incidence of infections of the udder, higher prevalence of lameness, and reduced milk quality [11,50–63]. Other conditions like the number of cows per stall, barn lay-out, previous experience with free stalls (early adaptation to the system), and the interactions between animals as well as with the farmer [64] should also be taken into consideration when designing a free stall based system.

The major components of a free stall (see Figure 1) are the surface for lying (the free stall base including bedding materials), the stall components defining accessible space laterally in stall (the stall dividers), and the rails intended to define lengthwise space in the stall accessible for the cow (curb, head-, and neck rails, and brisket locator).

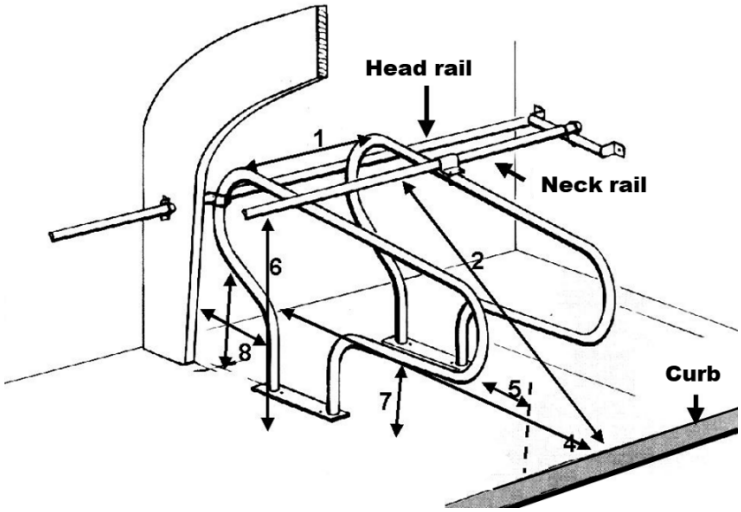


**Figure 1.** Schematic drawing of a free stall of a dairy barn. The numbered arrows indicate the dimensions as used by Irish and Merrill [65] (see Table 3). The head rail, neck rail, and the curb are described in Section 5.2.2.

### *5.1. The Surface for Lying (Free Stall Base)*

#### 5.1.1. Softness

The stall base can be made of different materials and construction, but has the main function of being a comfortable place for cows to rest or stand upon. Dependent on construction and type of divider, in many cases, it also functions as a basis for the fixation of stall parts. The general conclusion from the bedding preference literature, reviewed by Tucker and Weary [48], is that dairy cattle prefer softer surfaces. Preference testing provides information about cow choices, and these preferences provide insight into the features of the stall that are likely to be important to cows. Several experiments have shown that dairy cows have a preference for resting on soft surfaces [20,29,66–79] and there also seems to be a close relationship between softer stall bases, increased lying time [49,76], and improved stall cleanliness [63,74]. Reasons for preferring soft floorings may be found in improved comfort due to reduced contact pressure to protruding body parts when lying, improved friction when raising [80,81], but also reduced heat loss in cold climates [71,80]. In contrast, in a warmer climate, there have been discussion as to whether bedding materials with high thermal conductivity would be beneficial [82,83], and a preference for "cold" limestone over for instance "warm" wood shavings has also been found [84]. This illustrates that the choice of bedding could also be used as part of heat stress abatement strategies. Ortiz et al. showed that the use of forced cooling is preferred by the cows during warm periods [82]. A comfortable stall base in a free stall that allows for normal lying behavior is important to ensure that the cows choose to use the stall for rest, sleep, and rumination and also reduces the risk for cows to get lesions or other damage to their body [43,85,86]. If the flooring in free stalls is comfortable, the cows also produce more milk [15,87,88] because the mammary blood flow increases during lying by 25–50% [85], which is correlated with milk yield [86]. Lying costs less energy and is preferred over standing idle by cows. The time spent ruminating is also maximized when lying [87].

Cows drop down on one of their carpi when they are going to lie down [7]. The maximum load at each carpus is approximately 2 kN during rising or lying down movements [71,80]. Because there is not much subcutaneous fat in the knee, there is no cushioning of this force, resulting in a rather painful event for the cow if the floor is hard. Thus cows will become reluctant to lie down, resulting in reduced lying times. Flooring properties including the amount of bedding are important in this respect [3,49,89]. A quick test of the softness of the bedding is to let oneself drop quickly on the knees. This 'knee test' should preferably be executed by the farmer. If it hurts for the farmer, it will also hurt for the cow. This is usually a good way of convincing farmers to improve the bedding,

however, the test is subjective. In order to provide a simple and objective method for measuring stall base softness, Nilsson [71] expressed softness as mm impact of a sphere (diameter = 100 mm) at 2 kN load, a method adapted to a sphere with the approximate diameter of a cow's knee (diameter = 120 mm) by ADAS [88], and still used in standardized tests performed by DLG in Germany [90]. The method was also adapted to softer surfaces than mats (e.g., sand and straw) by Tucker et al. [89], known as the mixing bowl method. Recommended softness of a stall base is a minimum 16 mm impact of a 120 mm sphere at 2 kN load [37,80], preferably more than 20 mm. Ruud et al. [15] found increased softness to be associated with increased milk yield, reduced incidence of mastitis, and reduced number of involuntary removals in a survey in 232 free stall dairy herds. Cows housed on multilayer mats and mattresses in that study had 1.1% to 5.8% higher milk yields than concrete lying surfaces. This is similar to results of Calamari et al. [91]. Other studies have not found similar effects (e.g., Bewley et al. [92] and Fregonesi and Leaver [33]). The number of teat lesions dropped dramatically with flooring softness >8 mm impact, and the number of involuntary cullings dropped with increased softness, indicating a longer life span [15].

#### 5.1.2. Friction

Cows should be able to lie down and stand up easily in the same way as they do on pasture, hence they should have sufficient grip in the stalls [93]. A bedding that is rough could, however, easily cause abrasion of the skin and lead to injured hocks (Figure 2) or other injuries [94]. Some abrasive materials, like sand, are not abrasive when applied in a thick layer (>10–15 cm) and even sawdust, which can be considered as soft and non-abrasive, becomes abrasive if there is only a thin layer (a few millimeters) present [95]. It is thus important to provide enough bedding material independent of the type [3,96]. Amount or depth of bedding is also a question regarding cost as well as management. When worn, concrete floors are a major risk factor for trampled teats due to insufficient grip [97]. Cows frequently stand in stalls for shorter periods, hence properties related to "standing stability" (firm and with good friction) are of importance. Such properties are not studied in detail in scientific studies known to us.

**Figure 2.** Abrasion of the hock of a dairy cow due to bad or insufficient bedding material in the free stalls.

#### 5.1.3. Bedding Materials

A large variety of flooring materials are available and in use (see Table 1), however, the selection of bedding is often decided according to local availability. Bedding could be described according to the physical, chemical, and biological properties [98]. Bare concrete is too hard, and not recommended. It is even forbidden as the only stall flooring in some countries (e.g., in Norway) [99]. Most of the modern types of stall surfaces are soft enough to fulfill animal demands (e.g., rubber filled mattresses, waterbeds, and rubber mats that have a structure providing cushioning), whereas for some older products (i.e., compact rubber mats), the lying comfort is often at a non-acceptable level for use in a free stall. Acceptable softness could also be achieved by using loose bedding materials like sand, straw, or sawdust, when provided in a thick layer [96]. Cows clearly prefer lying surfaces with more bedding, and they spend more time lying down in well-bedded stalls than in those with little or no bedding [29,49,89,100,101], likely because this provides a softer lying surface [81]. Thin layers of sand may reduce the time spent lying with 2.33 h compared with a thick one [96].

Bedding serves two purposes. First, it softens the floor in order to improve comfort and welfare of the cow. Second, it keeps the cow and the area they lie on clean. This is best achieved when bedding is dry, as also preferred by the cows [102]. The comfort of a stall will depend greatly on the type, amount, and quality of bedding in the stall [3,93]. Optimal bedding should provide adequate thermal insulation or cooling (depending on the temperature), an appropriate degree of softness, an appropriate degree of friction, a low risk of abrasion, and should be easy to maintain and clean [82–84,103,104].

**Table 1.** The table describes flooring types categorized according to typical softness, and illustrates plausible consequences of flooring softness for the dairy cows.

| Flooring Type | Softness [1] (mm Impact) | Plausible Consequences |
|---|---|---|
| Concrete | 0 | Increased risk for teat lesions, mastitis and involuntary removal. Short resting time. Decreased milk yield |
| Compact rubber | 5–10 | Increased risk for mastitis and involuntary removal. Short resting time. Decreased milk yield |
| "Knob" mats | 10–15 | Increased risk for skin lesions. Somewhat short resting time and decreased milk yield |
| Softer structured rubber mats and multilayer mats | 16–30 | Normal resting time, udder health, milk yield, etc. |
| Rubber filled mattresses | 20–40 | |
| Water bed | >40 | |
| Sand | >40 | |
| Deep straw | >40 | |

[1] Softness is indicated as mm impact of a 120 mm sphere at 2 kN load [103] and according to the "mixing bowl method" [88].

Bedding should also be dry and clean in order to prevent the growth of bacteria [63]. Cows show a clear preference for dry bedding over wet material [101]. It is, therefore, important to cover soft cow mattresses with a layer of sawdust, straw, turf, ground limestone, etc., just to keep it dry and clean [100]. In this respect, the water holding capacity of the bedding material is important [98]. However, sand does not absorb water or liquids. It just drains to the bottom of the free stall and thus keeps the top layer dry. Whereas the top layer of an absorbing material will stay wet and needs to be replaced frequently. Adequate ventilation increases the evaporation of the moisture and thus contributes in keeping the bedding dry. A simple way of finding out in practice if the bedding is dry enough is when doing the knee test for softness (see Section 5.1.1), where one stays on the bedding for 10 s with all the weight on one knee. If the knee remains dry, the bedding can be considered as dry enough. In general, a regular (minimal twice a day) cleaning and refreshing of the bed-

ding is required, however, this is also dependent on the stall design. Most bedding material used is made of organic compounds and is, therefore, a risk factor for the growth of bacteria unless dry [61,93,105–108]. A high bacterial count in the bedding can be a risk factor for the development of mastitis [52,55,58,109,110]. However, the major problem increasing the incidence of lameness, mastitis/SCC [50,58,59,61,62,111], and inducing a higher bacterial count in the bulk milk tank [61,63] is probably contamination of the bedding with manure.

The most used loose bedding materials are straw, sawdust, recycled manure solids, sand, and ground limestone [93]. Other loose materials in use are shredded paper, wood chips, horse manure, and other wastes of organic material. Sand and ground limestone are inorganic materials commonly associated with low bacterial counts in the bedding, given that the bedding is sufficiently clean [61,108,110]. One ideal bedding material for all farms does not exist, since every farm has its own characteristics according to location, management, size, etc., and availability of certain materials, like sand, or the type of farm, ultimately determine the choice of the farmer. Organic farms, for example, focus more on the nutrient content of the manure and thus straw is preferred over sand. Hence, it is normally more important to consider the traits of the selected bedding (e.g., soft, dry, and clean) than the choice of bedding per se.

### Straw

Straw is one of the oldest bedding materials. It used to be a waste product of the agricultural division of a mixed farm, however, these days, straw can be rather expensive in certain areas due to competitive use. It provides a soft and dry bed for the cows when applied and maintained properly. Straw can be used long or chopped. Chopped straw is easier to apply, but contains more dust and can sometimes be abrasive. When used as the only bedding material, it should be applied in a thick layer of a minimum 15 cm, but preferably 30–40 cm [89,112,113].

### Sawdust

Sawdust is used both as the only bedding material in deep litter beds or as a hygienical covering on other flooring materials. As for straw, if used as the only bedding material, sawdust needs to be applied in a thick layer of >15 cm (or >7 kg per stall) to act as a cushion [3,29,95,111]. The sawdust should be proper sawdust and not mixed with splinters. In order to keep the sawdust (or straw) on the free stall, a metal/plastic pipe or rubber strip of 15–30 cm height can be mounted on the rear curb of the free stall [114]. Sawdust should fill the bed up to the level of the retainer, otherwise cows may injure the dorsal sides of the point of their hocks quite easily [115].

Because sawdust has a high absorption capacity, it is often used to keep other bedding materials like rubber mats or mattresses dry. Sawdust is an organic material, and to keep bacterial count under control, it should be dry and clean. In a dry and cool environment, the growth rate of the bacteria is low, however, under common conditions, the bacteria numbers may reach their maximum within two days [59]. Hence, daily refilling of sawdust is recommended [63].

Daily change of the bedding in the rear part of the free stall will keep the bacterial count low [51], and a complete change of the bed should take place at least every week [105]. Manure and leaked milk should be removed at least twice a day. Storing larger amounts of bedding (e.g., in the front part of the free stall) is challenging, since bacteria will start growing from the moment it is in place and after some days, bacterial counts may be high, although the sawdust might still 'look' clean [58,59].

### Recycled Manure Solids

Manure can be separated by compression, and the remaining solids can be used as bedding material in free stalls. It can be used after processing (drum composting) or immediately after compression. Drum composting reduces the number of *E. coli* bacteria. Further drying by blowing air reduces the moisture content, but has no influence on the number of bacteria [17,110]. The bacterial counts in the bedding are reflected in those on

the teat ends and bulk milk [58,61]. It is, therefore, important to monitor the hygienic status and ventilation very closely. So far, no reports have been published about a higher incidence of mastitis or somatic cell count [17,110,116]. Advantages are the availability, and thus the use of thick layers in the stalls (>30 cm), which increases lying times, cow comfort, and welfare [89,110,115]. Disadvantages may be the high number of bacteria present in the bedding, and use in humid climates and/or poorly ventilated barns could lead to a high moisture content in bedding [58,61] as well as high air humidity.

Sand/Ground Limestone

Loose sand conforms to the shape of the body and when applied in a deep layer (>25 cm), it provides a good bedding material for the cows with high cow comfort and good udder health, however, the consumption of sand is high [115,117]. The amount of sand that has to be added on a daily basis ranges from 14–20 kg per stall [118]. The consumption of sand increases with filling level, however, proper maintenance is essential for good cow comfort. Drissler et al. [96] found that for every 1-cm decrease in sand bedding, cows spent 11 min less time lying down. In their trial, cows had access to free stalls with sand bedding that was 0, 3.5, 5.2, or 6.2 cm at the deepest point.

Sand bedding may also help to minimize stepped-on teat injuries. These teat injuries often occur during the rising of cows in stalls. In sand-bedded stalls, the claws move into the sand while the udder remains positioned on the sand surface, thereby lengthening the distance between the claw and the teats.

Because cows spill sand into the alleys, it also improves footing [96]. Therefore, the sand should not contain small stones. The sand should not be too fine either; after a while it will become hard like concrete [119]. On the other hand, large grains will be rough and can cause skin abrasions. Sand of good quality may reduce the number of hock lesions [61,98]. Instead of absorbing moisture, sand lets it filter easily to the bottom of the stall, thus keeping the upper (contact) level dry. Since sand and ground limestone are inorganic, they provide a poor environment for the growth of bacteria (if clean), which is reflected in the bacteria numbers found on the teats of the cows [58,110]. This advantage, combined with good cow cleanliness and that it also provides cooling during warm summer months, makes it a popular choice of many dairy producers (e.g., in the USA).

The major disadvantage of using sand as free stall bedding seems to be manure management. Sand can settle to the bottom of manure collection pits, storages, and spreaders, making removal difficult [120]. It is, therefore, not a good option in combination with slatted floors, which are common in various countries like the Netherlands and Norway. Sand is abrasive and can cause excessive wear on manure scrapers, pumps, and separators. To keep more bedding in the stall, a pipe/strip at the rear end of the stall or so called sand savers can be used [119].

Ground limestone is soft and inorganic and is often mixed with sawdust or wood shavings to improve the moisture absorption. When used pure, the pH of crushed limestone is relatively high (7.91). This resulted in a low growth rate of bacteria in a study by Janzen et al. [110], but this may also result in teats with a dry and irritated skin. 'Sprinkling' crushed limestone over the free stalls to reduce bacterial growth, however, does not result in a proper distribution through the bedding material and therefore does not have the desired effect on bacterial growth [110].

Rubber Mat

Rubber mats have been widely used for decades. The quality and comfort for the cows varies between the brands. In general, mats that get old tend to acquire very small fractures, which can become sources for bacterial infections (environmental mastitis) [57]. Care should be taken that the mats do not buckle. Most of the older types of mats are made of solid rubber and are rather firm, however, when applied with sufficient sawdust or sand on top (>5 cm), they can result in a moderately comfortable bed for the cows [114,121]. Rubber mats with rubber protrusions underneath ("knob mats") provide better cushioning compared to compact rubber mats, and new and softer types are steadily being introduced

into the market, many of these softer than 20 mm impact. Soft lying mats are equivalent to straw bedding in terms of resting time, but less favorable with respect to leg injuries located in the tarsal joints, according to Wechsler et al. [122].

Cow Mattress

Cow mattresses are a compromise between comfort for the cow and the amount of work and money spent by the farmer [123–127]. The original mattresses were big bags filled with straw, wood chips, corn stalks, ground cork, or rubber. They were comfortable for the cows when new, but after a period, dents tended to be created because of uneven load distribution [128–131]. Therefore, the modern mattresses have a structured base by a quilting procedure. Most mattresses these days are made of tubes of nylon fabric filled with ground rubber (e.g., from recycled car tires) or plastic foam. The tubes are placed parallel and a fabric covering is put on top [128]. Mattresses as well as the top layer are available in many different types, thickness, and qualities. If dents are formed after a few years of use, the cover can be removed, and the tubes reshuffled. The cover can be placed again, and the cows have a comfortable bed for another number of years. On top of a mattress, a layer of sawdust or other absorbing bedding material is needed to keep it dry and clean [63]. A thick layer of saw dust (7.5 kg per stall) improves lying comfort [103]. In general, both multilayer mats and rubber filled mattresses provide proper comfort for lying. However, bare mattresses result in more hock lesions than deep-bedded sand or sawdust [11,115,129].

Waterbed

Waterbeds are rubber bags filled with water. They are not heated. Lying comfort is good, however, during lying down or rising movements, the cow places most of her weight on the carpi, pushing the water away, which may be painful, depending on the base of the waterbed [81]. Dual waterbeds have a small chamber in the area of the carpi to avoid this problem [132]. When the cow leaves the stall, the water mattress regains its rounded shape and all liquids on the top of it, like leaked milk, will run down onto the alley. Bedding should be used to absorb the remaining humidity. In this way, it may prevent bacterial growth and thus mammary infections. Normally, cows need a few days to get used to the feeling of the waterbed when entering the free stalls, and some cows prefer sand and certain mattresses over waterbeds [133,134].

### *5.2. Space—In General*

The dimensions of free stalls are of importance for animals, as resting behavior and preference is influenced by stall size [3,121,135]. Size appeared to be more important than softness of the bedding for cows [21]. In a stall that is too small, a comfortable resting position is impossible (Figure 3) [3,136,137]. In the last decades, the body size of the dairy cows has increased substantially. However, the dimensions of the free stalls have not been adjusted accordingly on many farms; this is particularly a problem in older barns [136]. An overview of some of the recommended dimensions is presented in Table 2. The importance is well illustrated by Tucker et al. who investigated the effects of stall dimensions [135], neck rail position [22], and brisket board [137] on preference and stall usage. Therefore, stall size should match the size of the cows (Table 3). The basis for Table 3 is not well documented by the authors [65], however, it is commonly used and should preferably be updated in a scientific study. However, to base the design on the mean size of the cows in the herd means that the space will be too small for the bigger cows [72]. Free stall dimensions have to be selected based on the 20% largest cows of the herd. Since body size varies between breeds, it is obvious that stall size also has to be adapted to the breed; the same stall size will not work for both Jersey and Holstein Friesian. A uniform size of the herd is a prerequisite to offer the optimal stall size for as many animals as possible. It is also suggested that less attractive stalls (usually in the end of rows) should be 10% wider than other stalls, so "big" individuals could choose these ones [36]. To determine if the dimensions for free stalls are right, a careful look at the cows (behavior,

posture, cleanliness, condition, bruises, hairless patches, and injuries) and the cleanliness and shininess of dividers and neck rails (meaning not clean or shiny) may confirm that the chosen dimensions are good [97,138,139]. Finally, one should be careful to assess single stall design parameters isolated from the others. A restrictive stall front design is associated with a higher need for lateral space [136]. The location of this lateral lunge space depends on the length of the free stall. It should be placed in such a way that the cow has an easy, natural access [117].

**Figure 3.** A free stall that is too short and narrow. The neck rail is shiny, indicating a restricted position. Furthermore, there is no lunge space due to the front wall and, finally, not enough (clean) bedding material.

**Table 2.** Recommended free stall design for dairy cattle. All measures in meters.

| | **NFA [1] (550 kg)** | **Norw. Rec. [2] (550–650 kg)** | **CIGR [3] (550 kg)** | **Anderson [4] 1st Lact (700 kg)** | **McFarland [5] (550 kg)** |
|---|---|---|---|---|---|
| Free stall length–wall | 2.40 | 2.60–2.70 | 2.39 | 2.74–3.04 | 2.34–2.49 |
| Free stall length–free | 2.10 | 2.40–2.50 | 2.06 | 2.43–2.74 | 2.03–2.19 |
| Free stall Width | 1.14 [6] | 1.14–1.19 [6] | 1.12 | 1.21 [6] | 1.03–1.09 [6] |
| Neck rail–height | 1.10 | 1.10–1.15 | "Not to low" | 1.22 | 1.07–1.17 |
| Neck rail–diagonal | - | 2.0–2.1 | - | - | - |
| Neck rail–horizontal | 1.6–1.7 | - | - | 1.73 | 1.58–1.63 |
| Upper head rail height | 0.8–0.9 | 0.95 | >0.73 | 0.86–1.02 | - |
| Lower head rail height | <0.2 | <0.1 | - | Absent | - |
| Brisket board height | 0.10 | 0.07–0.10 | - | 0.10 | 0.10–0.15 |
| Brisket board length | 1.70–1.80 | 1.80–1.90 | 1.63 | 1.78 | 1.58–1.63 |
| Rear curb height | 0.15–0.25 | 0.20–0.30 | 0.15–0.20 | 0.20 | 0.30 |

[1] From guidelines for Norwegian regulations on keeping cattle (NFA [140]); [2] Ruud et al. [37]; [3] CIGR [141]; [4] Anderson [142]; [5] McFarland [143]; [6] Center to center measure converted to inside measure by subtracting 60 mm for the thickness of the divider.

**Table 3.** Minimum free stall dimensions in relation to cow size. After Irish and Merrill [65].

| Dimension and Location | Animal Dimension |
|---|---|
| 1. Width (center to center of partitions) | Twice hip width |
| 2. Distance rear of curb to neck rail | Body length (rear of pin bones to brisket) or 210 cm (mean) |
| 3. Distance rear curb to open front | 1–1$\frac{1}{4}$ body length |
| 4. Distance rear curb to closed front | 1–1$^{1}/_{3}$ body length |
| 5. Clearance rear of curb to rear of partition | At paunch height, $\frac{1}{2}$ hip width or less |
| 6. Height stall bed to neck rail | $\frac{3}{4}$–$^{4}/_{5}$ shoulder height |
| 7. Clearance beneath side rails for legs and to block hips | $\frac{3}{4}$ hip width |
| 8. Clearance between rails for head (lunge) space | Hip width |

#### 5.2.1. Lateral Space—Stall Dividers

The function of the divider is to define the width of the lying place and separate lying places from each other, and works as a visual tool to guide the animals into the stall. The divider prevents the cows from lying diagonally, offers a degree of protection from other cows because it represents a physical separation permitting closeness of other cows without aggressive interaction [25], and also prevents animals from turning in the stall [65].

Dividers should not hinder the cows in any situation. The partition should be firm, smooth, without sharp bolts or nuts sticking out. The design should be such that the cows cannot get stuck under it, and should also provide enough lunge space [26,130,144]. The distance between dividers define stall width and is of importance for how the cow can use the stall for different resting positions. Bad design of the dividers and/or incorrect placing (too high or low) can induce bruises on the sides and backs of the cows [95,144]. The space dairy cows need for lateral movements ranges from 60 to 110 cm at the hips (this equals twice the width of the hip) [65,145].

Regarding stall width, Anderson [144] gives a summary of various recommendations. It is clear that a large variation exists (e.g., recommendations for cows >680 kg vary from 109–132 cm). Tucker et al. [135] reported in a study with non-lactating cows that the size or spatial arrangement of bars within the stall may be reducing lying time by around 2.5 h/d or result in cows that lie in the alleys. They also found that cows spent an additional 42 min/24 h lying in stalls measuring 132 cm in width compared with only 106 cm between partitions. Free stall width also influenced the time spent standing with the two front legs in the stall; cows averaged 58 min/24 h in stalls measuring 126 cm and 85 min/24 h in narrow (106 cm) stalls. The length of time spent standing with all four legs in the stall tended to be longer in the wider stalls (126 cm) and these were also most soiled with feces. However, the SCC increased in narrower free stalls [63].

Many recommendations for stall dimensions relate to the size of the free stall directly to the body size of the cows (Table 3 and Figure 1) [65,146]. In a study of Ceballos et al. [145], cows used up to 109 cm (180% of hip width) of lateral space when lying down. This is within most recommendations that, in general, advise 120–125 cm stall width for Holstein Friesian cows [138]. Pregnant cows, however, are wider, and a recent study of videotaped cows (Holstein-Friesian) in a straw yard showed the need for 137 cm of width, indicating that the width of the free stalls for pregnant cows should be wider than for other cows (van Eerdenburg, unpublished results).

Choosing yielding rails or free stall components is probably positive with regard to lesions due to a lower contact pressure to the body of the cow [147]. The number of lying bouts and their duration could provide more information relating to the ease of movement of the cows within those stalls. In a study with vertically positioned elastic partitions used in tie-stalls, Aland et al. [148] found that the partitions influenced stall cleanliness and lying position. Wandel and Jungbluth [149] utilized a free swinging horizontal wooden plank as a free stall divider and found this construction to gently and effectively guide the animals into the stall. Gwynn et al. [150] found that dividers with a rope replacing a fixed bar were preferred by the cows above the original fixed version. Even though cows preferred flexible dividers over fixed ones, no difference in lying time was found [25]. In an

experiment with flexible dividers, Ruud and Bøe [25] found that if the stall front is "open", allowing forward directed rising movements, the cows very seldom came in physical contact with the dividers during lying and rising movements. Whether the animals collide with the divider during lying and rising movements may also be influenced by the width of the stall and such potential confounders should be taken into account more thoroughly. Scientific knowledge on such effects of free stall divider design is, however, scarce, and the development of free stall dividers seems to be mainly industry driven [25].

#### 5.2.2. Lengthwise Space

##### Curb

The curb (see Figure 1) forms the border of the free stall. It can be made of wood, concrete, or metal. When entering the stall, normally the animals also have to take a step upwards. The function of this rear curb, besides partly defining the length of the stall base, is to elevate the free stall base and separate it from the normally wet and dirty floor in the alley in order to improve stall cleanliness [151]. Based on practical experiences, recommended height of the rear curb is 0.2 to 0.3 m [36,37], however, the scientific knowledge on rear curb design seems to be scarce.

##### Head Rail

The head rail (see Figure 1) is part of the construction of a row of free stalls. It forms a barrier for the cows to 'walk through' a free stall when there is no wall in front. Stall dimensions and design should provide the cows with sufficient accessible space for the normal forward lunging movements occurring during normal rising [145]. When lying down and rising, cows make use of a series of instinctive movements with a clear direction forward. This is because the cow's body is heavy, and the cow needs to stretch her head forward to act as a counterweight when she lifts the hind part of her body [1]. The lunge space (in front of the brisket board, if used) is the space taken up by the head of the cow as she moves forward to stand up. Cinematic analysis of standing up movements indicate that dairy cattle use between 260 and 300 cm of total longitudinal space (from the nose to the most caudal point of the cow) [152]. Based on the longitudinal movement of the nose, the space used by the head while lunging (in a normal rising situation) ranges between 22 and 72 cm [145]. It is worth remarking that the recommended total length of stalls ranges from 218–305 cm, with a majority of around 240 cm, instead of the required 260 to 300 cm [138,144]. This is measured as the distance from the rear curb to the head rails or wall. Reasons for and consequences of this "lack of space" between "unrestricted rising movement" and "recommended stall length" have, however, been scarcely investigated.

In stalls with limited length or a closed front, the cows may stand for a prolonged period before lying down (e.g., with two feet in the free stall), repeatedly sniffing the ground, and moving their heads left and right [76]. This is a stressful situation when she is motivated to lie but this is prevented by obstructions in front of her. This cow may also make use of abnormal movements, like trying to get up by rising on the front legs first (rising like a horse). The position of the head rails (the stall front) are, therefore, of special interest when discussing stall design. In such restrictive stalls, normal rising or lying down movements may be hindered due to the lack of space in front of the cow. The space used for such instinctive movements is defined by Baxter [153] as dynamic space. The problem with stalls with limited space for such movements, is especially evident for a row of stalls along walls or in stalls with a position of head rails that restricts forward lunging [154]. No head rails should be positioned between the top of a brisket board and 0.7 m above the floor, which should be preferably 1 m [139]. If space is limited in front of the animals, they need space to lunge sideways, and the divider should not block this space. The early types of dividers were usually problematic in this respect. Forward lunging is, however, strongly preferred over sideward lunging [145,152].

Neck Rail

One of the functions of the neck rail (Figures 1 and 4) is determining the position of the cow when she lies in the free stall. It should be positioned in such a way that the cows do not lie down too far into the stall, leaving some lunge space in front of her [93,142,155]. At the same time, as the cows should not be able to defecate/urinate in the free stall in a standing position, the neck rail should not hinder the cow when she wants to lie down [93]. This implies that the cow should be able to stand with all four feet in the stall without touching the neck rail [22,120]. A neck rail that is too high will result in dirty free stalls [50]. A general recommendation with Holstein-Friesian cows is to place the rail >210 cm from the rear curb (2 in Figure 1) and >122 cm above the stall bed. Furthermore, a position too far from the curb may induce diagonal lunging in the stall [142]. The accurate positioning of the neck rail is, therefore, a delicate job [22,47,154–156]. The size of the cows is very important in this respect, and a large variation in the size of the cows within a herd complicates a proper positioning. A practical approach that may tell us whether the position is good for most cows in the herd, is to check if the stalls are clean and that the cows are without injuries or abrasions on the withers. If the neck rail is shiny due to repeated body contact (Figure 4) and/or the cows have abrasions on the withers, the distance to the curb is too short or the neck rail too low [47]. If the free stalls are dirty and the neck rail is not shiny, the distance to the curb may be too large. Another way of determining an optimal position was performed by Ruud et al. [97,139] using an epidemiological approach. A total of 3459 stalls in 232 herds were assessed for cleanliness, and stall measures were recorded. In a statistical model, it was found that the cleanest stalls were with a neck rail position 1.96 m from the rear curb (measured diagonally). The main breed in that study was the Norwegian Red dairy breed with a body weight of 550–650 kg.

**Figure 4.** Shining neck rail of a free stall due to frequent contact with the cows.

There seems to be an established truth that more restrictions equal cleaner cows [47], however, speculations also exist that too much restriction will stress the cow, making her defecate more frequently. This is, however, scarcely documented [111,144,157]. A neck rail position that is too restrictive influences behavior (e.g., time standing with all four feet in the stall) and also increases the prevalence of lameness [47]. A properly designed and positioned brisket board may be a part of the solution, because it positions smaller cows while lying with less interference with normal rising movements.

The head and neck rails are usually made of a steel pipe (diameter 50 to 60 mm), however, one may also utilize flat nylon straps, chains, or wooden planks. To increase stall comfort, the contact pressure between cow and rails should be kept as low as possible. One should, therefore, in addition to location, choose profiles with large diameter, with rounded edges or utilize parts with elastic properties [142].

Brisket Board

The brisket board (see Figure 5) is a structure in the front part of a free stall that should position the cow as she lies down in such a way that the stall stays clean. It can be made out of plastic, wood, or concrete. A well designed and placed brisket board allows a placement of the neck rail [154] that is more forward. However, we raised the question of whether it should be placed a little bit further from the curb than commonly used measures today, for example, >180 cm from the rear curb for medium sized cows [139], and probably close to 1.9 m for larger Holstein-Friesian cows [142]. A short lying space makes lying down and standing up difficult and increases the risk for injuries to the tarsal joints [136]. The top of the brisket board should not be more than 10 cm above the level of the bedding and it should be smooth to prevent skin abrasions [137,152]. High brisket boards can hinder cows' rising and lying-down movements and may also hinder the cow in stretching a leg forward as can be seen in Figure 5. In deep litter stalls, the brisket board can also be situated underneath the level of the bedding material, with fewer restrictions for lying down and rising movements [157]. A free stall can be designed without a brisket board and still provide good cow comfort and stall usage [137].

**Figure 5.** Cow with front leg stretched over the brisket board of the free stall.

*5.3. Slope*

It is reasonable to think that all levels of a slope will contribute in draining liquids away from the stall base, especially with a bedding that does not absorb liquids, like a rubber mat. In a study by Norgaard et al. [87], the cows tended to slide a little backwards when lying with a 4% and 7% floor slope, whereas with a −1% slope, the cows slid a

little forward, but there was no negative effect on the natural standing up or lying down movements. Increasing the slope of the cubicle led to a drier and cleaner rubber mat at a 4–7% slope, and it was concluded that the slope of the cubicle did not affect the total time spent lying down, the number of lying periods, or the duration of the lying periods. Based on these results, a slope of up to maximum 7% could be recommended, but further testing should be done under practical conditions. Common recommendations are 3 to 6% slope [37,158].

## 6. Further Considerations of Free Stall Design

### *6.1. Improved Options for Other Behavior*

As explained before, comfortable free stalls will lead to longer lying times and thus a longer occupancy of these free stalls [81,102]. This means that fewer animals (except those feeding, eating, etc.) will stand, walk, and thereby occupy space in the walkways where they perform other activities. In that way, soft stall bases and correct dimensions will also indirectly influence the possibility animals have for performing other normal behavior than lying as well as the function of automatic milking and feeding equipment due to less queuing, etc. If we compare a barn with a mean lying time 9 h to a similar barn with, for example, 14 h rest, there will be approx. 20% more animals walking around in the activity area. This will, of course, influence the function of the barn, however, this is a scarcely studied research area.

### *6.2. Cow Comfort*

An easy way to assess general cow comfort in the stalls is the cow comfort index or quotient [93]. It is defined as the number of cows lying properly in the stalls divided by the total number of cows present in stalls and multiplied by 100 [159]. Observations should be recorded 1–2 h before milking. It is recommended that no more than 15% of the cows should be standing idle in stalls at this time. This cow comfort index (also known as the stall standing index) is an easy way to determine if the cows are experiencing problems with the stalls, however, it provides no specific information about what causes the problem. Since proper rest is fundamental for animal welfare, welfare protocols commonly contain questions related to the resting place. Examples of protocols focusing on the comfort of the free stalls are the cow comfort score [160], welfare monitor [161], and the Welfare Quality® protocol [162], focusing on animal based indicators that result from the use of the stalls.

### *6.3. Economic Aspects*

Investments in welfare are often very profitable. A correlation between a combination of parameters positively related to free stall comfort and milk yield was found [160]. and it has been shown that a soft free stall base contributed significantly to fewer incidences of clinical mastitis, fewer teat lesions, and cases of lameness resulting in a lower involuntary culling rate and thus in a lower number of animals to be replaced [15,163,164]. Furthermore, free stalls that are soft and provide adequate space will increase the time spent lying and thus the milk yield [15,91,163,164]. Careful estimations show that softer mats and mattresses are paid back in two to three years and with increased animal welfare.

### *6.4. Future Perspectives*

Today, sensors and the Internet of Things have also reached the cow barn. There are sensors that record resting-, eating-, and rumination time. Such systems give the farmer or the researcher direct and individual based information about crucial welfare and health traits such as resting time, number and duration of lying bouts, etc. These traits are among the most important welfare indicators we have, and will give us the possibility to have early warnings about health, estrus, and welfare. They can be integrated in a system of precision livestock farming [34,165] where the computer can provide information about stall use, lying time, and number of lying bouts, which can be used to evaluate the quality of the free stalls.

Alternative loose housing systems for dairy cows without the restrictions of the free stall (e.g., open bedded packs, cow toilets and more) are also under development today [166], however, hygiene is still a challenge. Perhaps a combination of free stalls, pasture, and/or open packs, together with new hygiene techniques, might become a future housing system?

## 7. Conclusions

This review should assist farmers and advisors to come to an optimal design of the free stalls. Comfortable free stalls, which are adapted to the size and the demands of the cow, will give her the possibility to rest and show normal behavior. Comfortable environments are associated with higher milk yield, better udder health, better milk quality, and better animal welfare, and will also result in a better income for the farmer compared to environments not designed according to the cows' size and needs. Furthermore, cows that live in a well-designed environment will also stay healthy and have a longer productive life. To achieve this, a detailed focus on the design and location of every stall component is needed. On every farm, the behavior of the cow, together with signs of conflict between the cow and the stall, could be a good help in assessing the results of the free stall design. In general, the optimal free stall should first of all have a clean, dry, and soft floor, suitable to rest upon. A slope of the floor between 3–7% may help to keep the stall clean. The free stall should provide the cow with sufficient friction and sufficient space for normal behavior such as enough space to stretch their front legs forward, enough space to stand or lie on their side with unobstructed space for neck and head, enough space to rest with their legs, udder and tail on the platform etc., and especially to move their body forward (or secondly sideways) during the lying down and standing up movements.

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