ELSEVIER

Livestock Production Science 84 (2003) 157–170

LIVESTOCK
PRODUCTION
SCIENCE

www.elsevier.com/locate/livprodsci

A novel design approach for livestock housing based on recursive control—with examples to reduce environmental pollution

Bram Bos[a,b], Peter W.G. Groot Koerkamp[b,*], Karin Groenestein[c]

[a] University of Amsterdam, FMG/Political Sciences, Oudezijds Achterburgwal 237, NL 1012 DL Amsterdam,
and Wageningen UR-Animal Sciences Group (formerly ID-Lelystad), P.O. Box 65, NL 8200 AB, Lelystad, Amsterdam, The Netherlands
[b] Wageningen UR-Animal Sciences Group (formerly ID-Lelystad), P.O. Box 65, NL 8200 AB, The Netherlands
[c] Wageningen UR-Agrotechnology and food Innovations, P.O. Box 17, NL 6700 AA Wageningen, The Netherlands

Abstract

Emissions to the air and nutrient losses to the environment (ground water and soil) are inherent to the keeping of animals in high densities in animal houses and cause various problems to men and animal (environmental, health and nuisance). Traditional approaches in animal husbandry, and also the approaches to solve these problems, are often and primarily based on *unidirectional technical solutions*, in which control is exclusively exerted over both dead matter and living entities. As a consequence, each technical solution to a problem implies increased constraints for the animals involved or end-of-pipe solutions.

A novel approach is presented to combine the nature of animals with the prevention and reduction of environmental pollution based on *recursive control*. This approach is based on the presence, knowledge and use of the natural behaviour of animals and their interrelation in the population. It is claimed that order in complex systems like these can be the result of animal interactions with their environment as well, without detailed human and technical intervention and surveillance. A fundamental precondition for this is a considerable degree of *slack*, or play, in order to give animals the latitude to adapt to changing local circumstances in the animal house.

In this paper, we will outline and discuss this approach both theoretically and practically, using examples with elements that support the theory, like a straw-based group housing system for sows, an aviary housing system for laying hens, and the approach taken by a new concept for the keeping of fattening pigs (Hercules project). We end by drawing some general conclusions on the consequences of this approach for systems design and suggest a number of recommendations for design heuristics.

Keywords: Livestock; Housing; Design approach; Recursive control; Emissions; Slack; Latitude

1. Introduction

Modern animal husbandry is accompanied by environmental problems, caused by the high densities in which animals are kept. One of these problems concerns emissions. Emissions to the air of polluting substances like ammonia, methane, nitrous oxide and dust, and emissions to groundwater and soil, like nitrate and phosphate.

The traditional technological perception of these problems is to portray them as a matter of specific parameters to be more rigidly controlled. As a result, technical measures tend to be developed which add more controls to the system concerned. For instance, animals are confined to specific locations, which

---

* Corresponding author. Tel.: +31-320-238514; fax: +31-320-238094.

E-mail address: peter.grootkoerkamp@wur.nl
(P.W.G. Groot Koerkamp).

0301-6226/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.livprodsci.2003.09.012

reduces the surface where urine and faeces are dropped and high-tech measures like air-scrubbers are installed to convert emissions before they leave the system. As a result, not only emission parameters are controlled, but animal behaviour will be restricted as well. The confinement minimizes the interaction between husbandry systems and their environments and makes it look more and more like a high-security laboratory.

This design approach is typical for the way agro-technological development has evolved in the past decades. The approach is characterized by an ever more increasing number of technical controls in livestock systems, in response to challenges that just often were the (often unexpected, and undesired) consequence of the (productive) success of these systems themselves.

We propose to call this specific way of dealing with problems in technological systems the ‘unidirectional control approach’. This approach is fundamentally based on the idea that nature (both physical and biological) is principally noncooperative, unless it is forced to. Therefore, in order to reach certain goals (for instance, reducing emission) controls have to be added, and every new challenge requires new forms of control, which might eventually be the source themselves of a new series of problems.

For a long time, raising productivity was the one and only goal in the development of western livestock systems. The current crises in animal production however, an increased awareness of the environmental problems, an increased concern with animal welfare in society and concern with food security, force us to redirect our efforts towards technology development which serves multiple goals, as mentioned (Beck, 1997; Ketelaar-de Lauwere et al., 2000). These goals are likely to be in conflict with each other and may seem irresolvable, especially if we continue to take the route of the unidirectional control approach.

We think these new challenges to innovation in livestock production call for a new approach in designing livestock systems, which takes part from the self-augmenting cycle of an ever increasing number of controls. In the present paper, we lay the groundwork of an approach that we will call the ‘recursive control approach’. Essentially, this approach takes synergy between physical, technical, social and biological forms of ‘control’ as its starting point.

2. Conceptual framework: two ways of creating order in technological systems

Modern livestock production systems can be perceived as *heterogeneous technological systems* (Hughes, 1987; Latour, 1987): an ensemble of elements of multiple and diverse origin (physical, biological, technical) which are durably and closely knit together in a coherent and—for the most part—deliberately planned way, which together durably realise the dominant goal of the ensemble. This ‘dominant goal’ can be equalled to the main societal function of the ensemble.

As long as technological systems succeed in attaining their dominant goal they can be said to maintain a specific order. This order is the result of a specific arrangement of the different constituent elements—both living and dead—and their mutual interaction. The arrangement itself is *technological*, since it is consciously imposed and maintained by human hands and is at least partly based on knowledge-intensive rational planning. However, this neither implies that the ordered end result is a complete reflection of a blueprint, nor that the constituent elements and their respective interactions are necessarily of a technical nature.

These systems consist both of living and dead entities, which stand in various types of relationship towards each other. Biological and social relationships are just as well ways of creating order as the technical ordering of things is. For instance, equilibrium balances in ecosystems can be said to represent order, but this order can very well be realised without human intervention or technology. The same holds for the stability within social groups, both human and animal. Order in heterogeneous technological systems is the result of the sum of quite different ordering mechanisms—physical and technical as well as social and biological. For instance, animal behaviour oriented towards the animal’s own needs, like feeding, mating and growing, is fundamental to the functioning of animal farming systems.

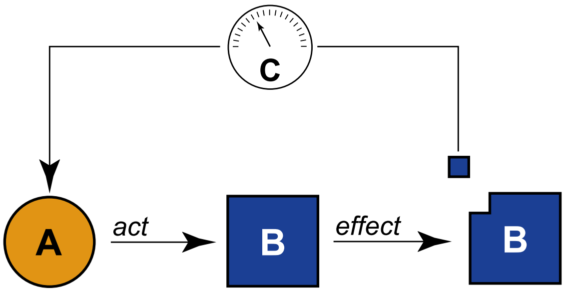
Mechanisms of creating order differ however fundamentally between living and nonliving things. Living things act and interact with a purpose; dead things do not. This purpose may be conscious, in which case we call it *intention*, but may as well unconsciously derive from the specific biological and psychological needs of living beings. In both cases, actions are generally performed in order to reach a result that feeds back on the actor itself. Therefore, living things relate to their surrounding environment in a direct, *recursive way*: their acts *matter* for themselves while the effect recurs directly upon the actor.

The action of inanimate—for instance technical—things, does not. Surely they are affected by other entities, and in turn influence others, but their actions never directly feed back on their existence. While most actions of living beings have an inherent feedback, regulation or control of the result of the behaviour of physical and technical objects always presupposes at least a third entity, connecting the effect of the subject's actions back upon it. Feedback thus has to be deliberately implemented, and in most cases via a third object or actor, like a thermostat adjusts the activities of a central heating unit to keep the room temperature within a predetermined temperature range. The difference between unidirectional and recursive control is graphically shown in Fig. 1.

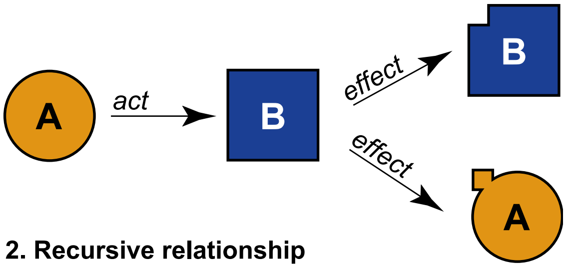
Living and dead entities thus relate to other objects in a fundamentally different way. Living beings can be said to relate primarily in a *recursive way* in which subject and object can be said to control each other mutually—be it in quite different ways. Inanimate things, like technical artefacts relate to other entities in a chain of one-way causalities, which might eventually be looped back to the beginning—a feedback that is to be implemented deliberately.

We dub these two different kinds of actions *recursive*, and *unidirectional*, respectively. Although these two types are strongly connected to either living or nonliving things, no essential differentiation is meant here. Technical things might be so cleverly designed that their actions are directly related to their existence, and living things may act like zombies, without any recursion of their actions towards their own existence. At this moment, these are however exceptions proving the rule.

If a specific act or class of acts from one entity towards another occurs continuously or in regular intervals, we may speak of a (structural) relationship. This relationship can be perceived as a form of *order*, and may be identified on the individual as well as the aggregate (group) level of species or sorts. For example, the well known symbiotic relationship between *Rhizobium* bacteria and species of the pea family *Fabaceae* is structural both at the individual as well as the group level. On the other hand, predator–prey relationships cannot be structural on the individual level by definition, but on the group level, they are. In both cases, however, the resulting order does not depend on a control measure from outside, but is based on the mutual dependencies between the actors or populations of actors involved.



1. Unidirectional relationship with feedback



2. Recursive relationship

Fig. 1. Graphical representation of a *unidirectional* (1) and a *recursive* relationship (2). In a unidirectional relationship, the act of A can only be influenced by its effect if the effect is deliberately fed back via a third process or actor C. In a recursive relationship, the act of A intrinsically has an effect on A itself, besides the effect on B. No third process or actor is needed. In both cases, order results, but under conceptually different conditions.

3. Organizing order

Livestock production systems are—as heterogeneous technological systems—composed of dead matter, technical artefacts, biological and social entities. Technical, physical, biological and social processes coexist and cooperate, even in the most high-tech examples of modern animal husbandry. The global order on the system's level is the result of the sum of local orders, established by this variety of processes. Some of these are under our control, while others are not. If this is true, the way we design these systems will differ fundamentally from the way we engineer technical artifices, since we have to integrate a diversity of mechanisms of producing local order, that are largely self-organizing. The extent to which we use either recursive or unidirectional mechanisms of control represents a basic choice.

The way we apply these mechanisms of creating order—or, the way we approach design questions—differs also. As the philosopher Andrew Feenberg showed with his 'Instrumentalisation theory of technology' (Feenberg, 1999), successful realisation and functioning of technology not only depends on the isolation, decontextualization and skilful reordering of objects and processes (primary instrumentalisation) but as well on the way these technical things are adopted and adapted into the wider context (secondary instrumentalisation). Technology functions only within a context that is never purely technical (Latour, 1987). Humans play a vital role in this wider context, but there is no principal reason why other beings could not (Latour, 1993).

However, engineering has traditionally focussed on the first element of realisation of technology, also in the design of livestock production systems. For a long time, a dominant supposition has been the idea that animals and plants had to be forced to comply with the goals set for these systems. The animals concerned were treated as technical raw material, to be controlled in a unidirectional way, while animal behaviour was primarily seen as a potential disturbing factor that was to be ruled out as far as necessary. This neglects the fact that animals do contribute to the functional order of the system, and underestimates their potential to do this even further.

Thus, if we want to benefit from this, another design approach is necessary, in which we use the different types of local order produced by recursive control as elements for the global order of the system. This implies that we adopt a perspective in which animals are seen as participants and co-creators of the system, rather than as elements to be contained and manipulated by the system.

We would like to conclude by highlighting two features of living beings that set a general condition for livestock systems based on recursive control: the capacity of living beings to exhibit adaptive responses, and their individual variability. One of the typical characteristics of recursive control is its ability to respond as it is to changing circumstances. Animals and plants possess a range of adaptive responses by which they can maintain their relation with other entities, or with their environment in general. One may think of the variegated responses to deal with drought or heat, aggression, danger, food shortage and stress. This range of responses is an essential prerequisite for maintaining the established order in the face of changing or varying circumstances. It is therefore necessary to provide the conditions for these adaptive responses. Moreover, just as circumstances may vary, animals do as well. Their individual needs and (adaptive) behaviour will vary likewise. This is a second reason to shape livestock systems in such a way that the animals involved can contribute optimally to the general order, by seeking to fulfil their own needs and express their own behavioural characteristics.

A general condition of livestock systems to accommodate and productively engage both features—variability and adaptive responses—is a considerable quantity of play, or slack. Slack denotes a balance between unidirectional control on the one hand, and a certain amount of freedom on the other. What is happening within this free space is essentially not put under (external) control. Here the way entities interact is—as a matter of fact—left to themselves. Our suggestion here is that we should deliberately and in a reasoned way increase the degree of slack in the design of animal husbandry systems, in a way which facilitates the emergence of (useful) order out of recursive interactions of the animals themselves with their environment.

4. Examples and comparisons: reduction of emissions and environmental technology

In the next two examples, we describe two different housing systems that bear significant marks of our suggested approach compared to more traditional housing systems. In these examples, we focus on a specific aspect, namely reduction of emission of ammonia from these systems. The comparison with traditional housing systems is meant to clarify our distinction between order generation based on unidirectional and recursive control, and to show why a considerable amount of slack is a fundamental condition for the latter. Evaluation of the housing systems in a broader perspective and for practical circumstances, e.g. on labour, economics or welfare, is on one hand not relevant to serve the purpose of this paper (present and illustrate a new design approach), and on the other hand the design of the examples is not (completely) based on the proposed new design approach, and consequently evaluation of the design method is not possible here.

4.1. Example 1: housing of sows

Emission of ammonia is caused by the decomposition by bacteria of urea and undigested proteins, present in urine and faeces, respectively. Since ammonia (NH_3) is a gaseous substance and only partly dissolved in urine (as NH_4^+), it will evaporate into air and leave the animal house, unless countermeasures are taken. In the environment, ammonia will deposit and eutrophicate and acidify the ground—and surface waters, thereby changing the local ecological circumstances. For this reason, ammonia is considered to be a polluting substance, which is to be prevented from entering the environment (Sliggers, 2001).

Reduction of ammonia emission is possible, among others, by preventing volatilisation by decreasing the surface area where manure and urine are in contact with open air and the duration of this contact (Aarnink, 1997). To realise that, we can confine animals individually in crates with a size that limits their possibilities for movement so we can limit the surface area where manure and urine are deposited to the back of the crate. If that part is constructed with a slatted floor the manure can be stored in a pit underneath. In fact this is exactly what is done in traditional housing systems for sows in the last decades, be it not inspired by environmental concerns, but established for hygienic and labour reasons. The ammonia emission from traditional individual housing system for sows is 4.2 kg/year per sow (Infomil, 2002), and can be reduced down to 1.8 kg/year per sow if the fouled area is minimized and manure is regularly removed to a closed storage system.

Although housing sows in crates is an effective solution with respect to emission control (as it was for hygiene and labour), the sow's possibilities for movement and interaction with her fellow sows are significantly constrained. In our conceptual framework, we could say that the sow is put under increased unidirectional control (by the crates). In order to solve a technical problem, the sow (among other entities, like crate and manure) is decontextualized, isolated and defined as a part of a small technical system, in which manure deposition and removal are more firmly under our control. Next, sow-and-crate are reintroduced in the wider context of the animal house, where the sow is allowed to give 'meaning' to her living environment, and find ways to cope with it, within the confinement of her crate.

Another way to solve the emission problem takes a fundamentally different route, with sows circulating freely within a group housing system (Fig. 2). In this housing system, sows have a common living area, divided in a set of functionally differentiated areas. About half of the total area is designated for lying which takes about 80% of the sow's time (A). The floor is made of solid concrete, covered with abundant straw. They can choose to lie apart from, or next to each other, on different spots within the area, which enables them to find the most comfortable position with respect to climate and social aspects. To feed or drink, they can enter other areas within the animal house (B and C), which are physically separated from the lying area by a small wall with an entrance in the middle. Sows may enter the feeding stations (in spot B) freely, but only get feed if the feeding computer grants it. Water however is available ad libitum in the drinking area, where sows are allowed if they are not separated at point D. Otherwise, they are led into the separation area (E), which lies next to the boar's pen (F).

The natural behaviour of pigs is to avoid fouling their lying and feeding area. As can be seen in the figure, only the waiting area before the feeding stations and drinking areas (B and C) and parts of the separation room and the boar's pen are equipped with slatted floors. The functional division of this area induces sows to take a specific routing when actively

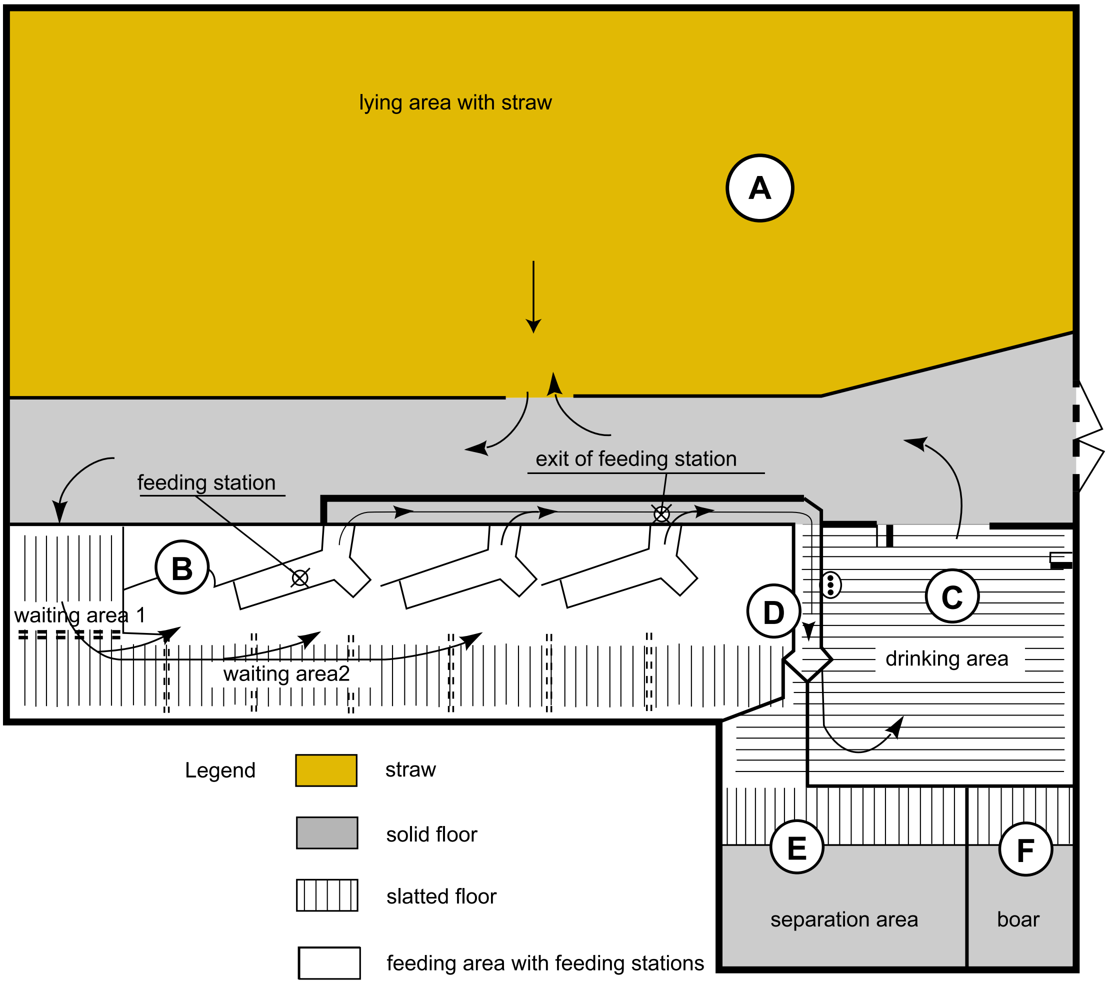


Fig. 2. Plan view of the layout of the so-called 'walking around house for pregnant sows with feeding stations and straw bed' (adapted from Groenestein, 2000).

going for food and water, and thereby succeeds in constraining the faeces and urine deposit to a specific (slatted) area. Additionally, the pit underneath the slatted floor in B is divided into compartments (indicated with dotted lines) to avoid faeces and urine spreading to places where it is not deposited. In this way, the surface area of the manure can be minimized without putting additional constraints on the sows themselves, as in the previous approach.

Here, the deposition of manure on specific spots (*order*) is established by a combination of unidirectional and recursive control mechanisms. The functional division of the different areas in the housing system does force sows to walk in specific directions to get food (concentrates) and water, but the initiative and the walk itself are up to themselves. Since the result of this act matters to herself, we call it recursive control. On the other hand, the ration of concentrates is limited by a computer. *Concentrate intake and timing* thus is controlled by the sow recursively, while *concentrate quantity* is controlled unidirectionally by the computer. The quantity is adequate from a nutritional point of view, but it does not satisfy feeding motivation (hunger) (Lawrence et al., 1988). Additionally, the sow can consume the straw in the lying area as a roughage. Again this is recursive control because whether, where and when the sow consumes straw, is up to her and the effect recurs directly upon her.

Our specific interest here is however not food intake, but emission reduction. Here, this reduction is attained on the one hand by the routing in the housing system, associated with the sow's individual activity. By allowing sows to consume concentrate when they need it, recursive control is introduced as a mechanism that results in the order of manure deposition at a specific place. But this is only one part of the story. The different design and physical separation of the lying area from areas where specific activities like drinking and feeding concentrates take place, enforces social behaviour among sows, directed at maintaining a clear separation between areas where manure is deposited, and areas where they are resting or eating. In this way, the already most obvious places to excrete urine and faeces become socially determined dedicated places to excrete urine and faeces. The ammonia emission from this type of group housing system is determined at 2.6 kg/year per sow (2.1 in wintertime and 3.0 in summertime; Infomil, 2002; Hol and Groot Koerkamp, 1999; Groenestein, 2000), being substantially lower than the 4.2 kg/year per sow for traditional individual housing. This is attributed to the reduction of the fouled area by directing excreting behaviour and by changing the manure composition by intake of roughage (Canh, 1998).

The social mechanism that directs behaviour is, however, a fragile balance that can be maintained only when the circumstances are optimal. Climatic conditions are important because they affect lying and excreting behaviour of pigs (Steiger et al., 1979; Aarnink, 1997). Climate control, both at the macro as well as the micro-level is therefore a necessary precondition to sustain this socially enforced balance. In this case, the macroclimate is regulated centrally and controlled with a computer to keep the air temperature and the air quality within a certain range. However, since the sows can move freely in this group housing system, they themselves can regulate the microclimate surrounding them, for instance by lying together when it is cold, or apart when it is warm, and by looking for the best places to stay. Thus, also here a combination of unidirectional and recursive control mechanisms add to the creation of order, in our case: a limited area where manure and urine are deposited, resulting in a reduction of emission.

Table 1
Overview of system characteristics, way of control and environmental parameters for two housing systems for sows

	Crate housing	'Walking around system'
Area per animal (m^2)	1.30	2.25
Type of housing	Tight in crate	Loose
Type of living area	One spot	Various functional places
	Feed trough per sow	Free accessible feeding station
Feeding system	Concentrates restricted No roughage	Concentrates restricted Ad libitum straw
Climate control	100% by computer and vents	Computer, vents and animal adaption
Temperature set point	19–21 °C	10–25 °C
Feeding control	100% computer	Sow's initiative
NH_3 emission (kg/year per sow)	1.8–4.2	2.6
Control of manure deposition	Fixed by crates	Group behaviour of sows and spatial layout

The difference between the first and second approach of reducing emission should by now be clear, which is summarized in Table 1. Sows are granted a considerable space and room to organize their activities: literally space to move, and metaphorically room to choose from their specific repertoire of actions based on their actual needs. The space and room are essential preconditions: without it the animals would not be able to maintain this order, and change their behaviour if the circumstances would force them to. This precondition is what we called slack earlier, which term may denote both physical space and behavioural room for actors within a technological system.

4.2. Example 2: housing of laying hens in aviary systems

Poultry farms face the same problems with emissions as pig farms do. In order to reduce emission, it is necessary to reduce the time manure is in contact with the air, or to control the composition of the manure and litter (especially dry matter content; Groot Koerkamp, 1998). Although the type of problem is the same, the solutions for hens differ from that for pigs because the chemical composition of the manure differs, but also because hens are not pigs.

In traditional housing systems, laying hens are kept in small groups in narrow cages made of wire floors, stacked in large rows next to and above each other (Table 2). The wire floor of these cages is tilted a bit, so that laid eggs automatically roll down to an egg belt next to the cage, by which they are transported out of the animal house. Hens are automatically fed with a feeding belt that delivers feed several times a day, controlled by a feeding computer. Since the floor of the cages is made of wire mesh, all manure falls through the bottom of the cage on a manure belt that removes all manure on a regular basis out of the animal house to a (closed) storage system. To reduce gaseous emission, many cage systems are nowadays equipped with a drying system, blowing warm air over the manure on the belts. To keep air temperature and air quality within a certain range, fans and inlet openings for air are computer controlled. Ammonia emission from traditional battery cages with belts (dry or wet manure) amount 42 g/year per hen (adjusted from 35) and reduction down to 12 g/year per hen can be achieved by enhanced manure drying and/or more regular removal (two–seven times per week) (Infomil, 2002).

Table 2
Overview of system characteristics, way of control and environmental parameters/production results for two housing systems for laying hens

	Battery cages system	Aviary system
Space per hen (cm^2)	550	Approximately 1000
Space characteristics	100% mesh wire floor	Various functional areas
Group size	Approximately 5	5000–25,000
Typical aspects of movement	Restricted to cage	Free between areas
Climate control	100% by computer and vents	Vents and computer + adaption by hens
Temperature control	20–22 °C	20–22 °C
Ammonia emission (g/year per hen)	12–42	20–90
Manure on belts (%)	100	90 (rest in litter)
Control of manure deposition	Fixed by cage	Belts placed where hens defecate most
Feed intake (g/day per hen)[a]	118	120
Egg production (kg/house hen)[a]	23.65	23.45

[a] Typical representative example taken from Groot Koerkamp (1998).

Again, this is an effective way of dealing with the inputs and outputs of these animals, but necessarily accompanied by heavy constraints on the hens involved. They have very limited possibilities for movement and behavioural repertoire, and social interaction is limited to their cage fellows. Moreover, boredom and stress increases pecking at each other, so that the hens' beaks have to be trimmed to prevent serious damage. Above all, the microclimate cannot be controlled satisfactorily. Climatic demands by the hens vary in time and between hens, while the local differences in temperature, drought, or freshness of air between cages may vary widely. These differences can neither be adjusted for by technical means, nor by the hens themselves, confined as they are to this particular cage on a particular floor in that particular corner of the animal house.

An alternative for the above described battery cage system is the aviary housing system (Blokhuis and Metz, 1995). Fig. 3 sketches a cross section of this system. Here, the animal house is divided into a number of large functional areas, between which hens can move freely. Several constructions of terraces or tiered wire floors, vertically positioned above each other, are positioned in the middle of the house. The lower floors are equipped with feed and water supply, while the upper tiers are equipped with perches, to serve as resting area. The floor between the construction elements is filled or covered with straw or sawdust at the beginning of a laying period, to serve as dust bathing and scratching area. Spreading of wheat in the litter area once or twice a day activates the hens to scratch and search for food in the litter. At several places, laying nests are placed for hens to lay their eggs.

One of the key aspects of this system is its vertical orientation. Hens are free to choose from different levels, a situation that fits with their natural behaviour: during daylight, they stay primarily on the ground, or at the lower levels, searching for food. At night, however, they will seek the highest place available for sleeping, safe for predators like foxes. This behaviour can be performed in the aviary as well. This

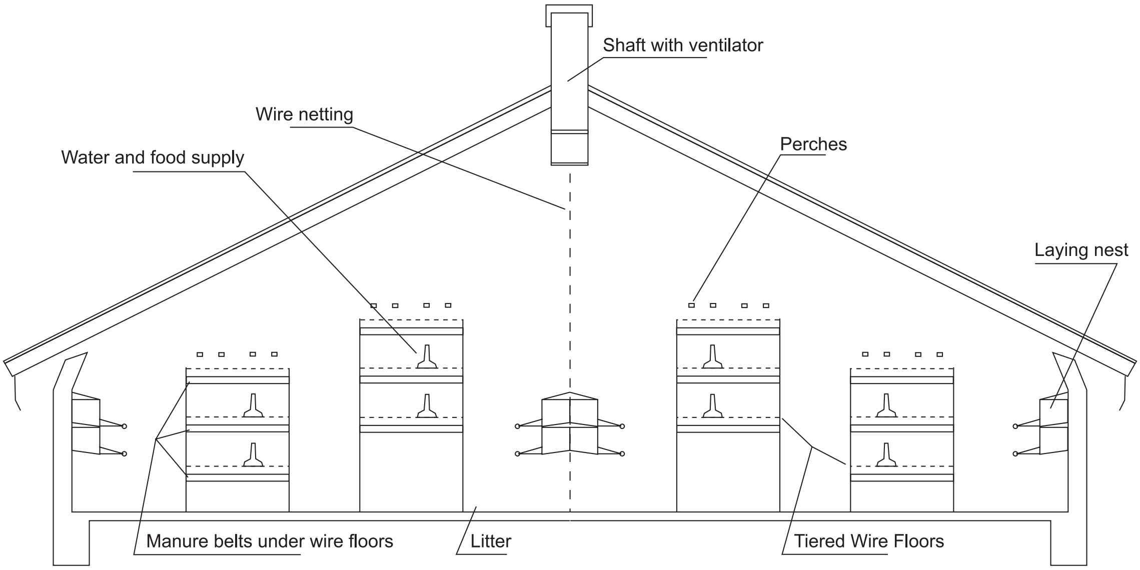


Fig. 3. Cross section of a typical aviary housing system. Adapted from Groot Koerkamp et al. (1995).

has the additional benefit that hens are able to look for the most comfortable place to stay with respect to the climate in the animal house (resulting from the ventilation and individual—and group behaviour) and social aspects (pecking order in the group).

Just as in the case of the group-housing system for sows, this aviary is built around behavioural characteristics of the animals involved. From the perspective of emission reduction, the performance of the system is quite good, despite—or rather: thanks to—the fact that considerable slack has been added by letting hens choose their position within the aviary freely. Since they spend considerable time on the terraces during daytime for feeding and drinking, and sleep above them on the upper tier at night, about 90% of the faeces is dropped on belts moving below these terraces. Despite the fact that hens, unlike pigs, do not have a specific behaviour related to defecating to maintain clean and filthy areas, this design succeeds in combining our two different ordering mechanisms in order to control emissions. On the one hand, hens are set free to perform much more of their behavioural repertoire, and choose from a variety of locations and heights. Since the hens perform these actions with a purpose for themselves (feeding, social behaviour, dust bathing, scratching, sleeping, egg-laying), order here is the result of the combined effect of the activities of the hens, without having to control it from outside. Chickens tend to fly to higher areas when they go to sleep, and they tend to look for the most appropriate place to feel comfortable. The design of this system is based exactly upon this, by positioning these places above the manure belts. These belts can be seen as one of the unidirectional control mechanisms completing this system, as the general climate control can. The fundamental difference with the above example of the cages, however, is that these unidirectional controls are directed mainly at dead matter (air, manure), not at the hens, while control of the stream of manure in the first case is essentially coupled to (unidirectional) control of the hens. Despite the success of the aviary design and manure removal by belts, the remaining 10% of faeces dropped in the litter area cause (relatively) considerable high emissions of ammonia, being 90 g/year for a typical aviary system. Research focussed on this problem (Groot Koerkamp, 1998) and showed that reduction down to 20 g/year per hen is possible through enhancing the scratching of the hens, which is stimulated by the spreading of wheat, and new ventilation systems to keep the litter friable and dry because the evaporation of water from the litter is enhanced. However, emissions exactly as low as the optimised battery cage systems are hard to achieve.

This example of the aviary shows, furthermore, that the normative requirement to free laying hens from rather awkward living conditions does not imply that all kinds of new high tech is needed to circumvent the potential drawbacks of this for the goals of the system. Often, animal welfare and economical and ecological requirements are portrayed as conflicting requirements. While we would not claim that the effort to attain these different goals in conjunction is easy, this example, as well as the example of the walking around house for pregnant sows outlined before, shows that providing slack, or letting loose, does not have to imply complete anarchy. On the contrary, if animal behaviour, oriented as it is to fulfilling its own needs, is taken as an ordering mechanism in itself, more synergy can be reached between animal and system goals.

5. Concretization as a generalized form of recursive control

Since recursive control is essentially bound to actions that matter for the actor himself, this particular way of generating order does not apply to dead matter. However, a key characteristic of establishing order by recursive control is that it makes use of mechanisms and processes already present before the engineer enters the scene. The technologist's challenge is to look for synergies between pre-existing ordering mechanisms and the system's goals, and structure the system in such a way that this synergism is elicited. Viewed in this way, the design approach sketched before can be generalized to the use of nonliving entities and physical–chemical processes, if we take the essence of this approach to seek for *functional compatibilities* between technologies and their environment, which consists both of biological, physical and chemical processes. Tangible examples of this are the air-cooled engine that lacks a separate cooling device, but is instead designed to convert fuel into motion and cool itself at the same time, or the solar house deriving its heat from incoming sun rays, instead of utilizing a separate heating device burning fossil fuel (Feenberg, 1999). In the first case, two separate structures are replaced by one, serving two functions at the same time. In the second case, an environmental process is integrated in the functioning of the structure. What connects these two examples is the more thorough integration of functions compared to alternative structures in which these functions are just added to one another. Cooling becomes a function of the structure, instead of a precondition for its functioning. The sun becomes a sense part of the structure of the solar house.

The French philosopher Gilbert Simondon (1958) called this integration of functions and environmental processes 'concretization'. Engineers would call it—for instance—the search for 'elegance' (Feenberg, 1999). In the next example, we shall show how this concretization works out in the case of a housing system for fattening pigs, aptly called *Hercules* since it is a smart and strong design to solve a range of environmental problems at once.

5.1. Example 3: Hercules: environmental technology based on natural processes

Hercules is the name of a housing system currently under development, in which it is tried to solve a number of environmental problems associated with the current intensive ways of fattening pigs for meat production, while at the same time complying with future standards for animal welfare (Ogink et al., 2001). This housing system, which is going to be tested on a farm scale (800 pigs) from the fall of 2002 to the fall of 2004, is aimed to be an integrated concept in which both physical and biological mechanisms at hand are used to drive other processes in the system. An overview of how these processes are integrated can be found in Fig. 4.

One of the main goals of the Hercules-concept is to reduce the environmental pressure of housing fattening pigs. In order to do this, the concept aims to close the cycles of energy and matter as much as possible, both inside the system itself and in relation to its environment. The system is designed on the one hand to make an optimal use of the by-products of the food industry, rest heat in the exhaust air and temperature dampening capacity of the soil, and on the other hand by processing separate streams of manure and urine (the natural by-products) in such a way, that their utility in agriculture is increased. In fact, under certain market conditions these outputs may even represent a genuine economical product in themselves, next to the meat produced.

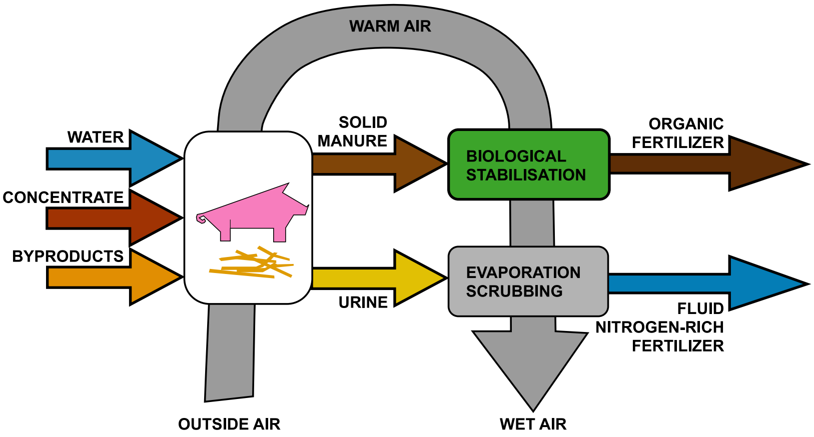


Fig. 4. Flow diagram of the Hercules concept: overview how processes and functions are coupled and integrated (Ogink et al., 2001).

In the *Hercules* concept pigs are housed in groups of 12 in pens in which 60% of the surface has a solid floor. The remaining 40% has a slatted floor. The pen design and climate circumstances are such that pigs tend to use this part of the pen for defecating almost exclusively—a biological ordering mechanism we already described in the previous example of the walking around house for sows.

Underneath this slatted part of the floor, convex belts were installed in the pilot test house that enabled so-called direct separation of faeces and urine (Ogink et al., 2001). Gravity causes urine to drip off into gutters alongside the belts, while faeces remains on the belt and can be removed daily. The resulting two streams then can be processed, respectively, by composting and evaporation, leading to a solid organic fertilizer on the one hand, and a liquid nitrogen-rich fertilizing substance on the other. Since faeces and urine have different proportions of minerals like N, P and K, both products can be applied in different agricultural circumstances—alone or in a variety of mixtures.

The energy that is produced by the pigs plays a pivotal role in linking the different processes within the system. Fresh air from outside continuously enters the animal house through the basement of the house in order to enable energy exchange with the soil with a stable temperature of approximately 10°. This stream of air is subsequently used to create a good environment for the pigs, dry the faeces on the belts as well as to evaporate the water from the urine and scrub it from odorous substances. The last two processes run in parallel within one installation, called an evapo-scrubber. Thus, four functions of the system are combined here: the necessary cooling of incoming air to keep the temperature within a certain range, the stabilization of the faeces, the evaporation of the urine and the scrubbing of the wet air to prevent emission of odor and ammonia.

Next to body heat as a source of energy for system processes, another source of energy is found in the biomass present in the faeces itself. Essentially it is this type of energy that is driving the composting process.

So, in the Hercules concept several existing products and processes are utilized within the system to drive other processes, in summary:

- The use of gravity to attain separation of faeces and urine—instead of a centrifugation unit;
- Benefit from the pre-given difference in composition of faeces and urine differs;
- Coupling of climate regulation with energy using and producing processes;
- Use of energy exchange with the soil beneath the building—instead of separate devices.

The description above showed our main point in this section, namely that the use of existing ordering mechanisms is not limited to biological mechanisms per se (as was the case in the previous two examples), but can be extended to physical and chemical processes as well. This approach is characterized by concretization, in which an engineer looks for functional compatibilities between processes within the system, and between the system and processes present in its environment. By integrating these functions in one structure, the number of add-ons and inputs needed to let the whole structure function properly can be reduced. As a result, the use of scarce resources is diminished. Moreover, it makes the system more self sustaining and less prone to failure, since a number of critical processes within the system depend on mechanisms available anyhow.

6. Discussion: a different perspective on the role of technology and engineers

The basic point of this article is that order in heterogeneous technological systems can be established by two mechanisms of control that are fundamentally different: unidirectional and recursive. Once living entities are on the stage in these systems, both mechanisms may be applied, together or alone. Due to their differences, the way in which they are realised differs also, as outlined in Section 3.

The crates or cages approach is exemplary of a design approach oriented towards primary instrumentalisation. In these cases, the animals involved are as much subject to decontextualization and isolation as the rubber bands, rollers and other metal parts of the belts are. They are taken as 'devices' or black boxes with a minimum set of relevant inputs and outputs that can be dealt with in exactly the same way as we would deal with inanimate matter, like air, dust or manure. Whether and how animals can deal with this situation (coping) is at best a concern after the principal design work is done.

On the other hand, in the aviary and the group housing system for sows, animals are actively involved in shaping the order of the system. They are not decontextualized and subsequently treated as raw material in a new context they just have to cope with, but the context is shaped around their natural behaviour in such a way that the order they thereby generate contributes to the system's goal. Secondary instrumentalisation, understood as living entities shaping and reordering a given technical artefact or environment, becomes an integral part and even a starting point of the design process itself.

In the latter approach, pre-existing biological mechanisms and functions are welcomed and optimally used, rather than neglected, constrained or even broken down as is the case in the first approach. This idea was generalized to nonliving entities in our last example of the Hercules concept, where pre-given physical and chemical mechanisms are used by looking for functional compatibilities. With this distinction in design practices we do not mean to say that 'isolation' and 'decontextualization' are wrong in general. On the contrary, they are a useful and necessary part of technological engineering heuristics and practices. We only think that design practices in the past have been based too much on the premise that the only way to get a properly functioning system is to treat animate and inanimate entities in this same way. We tried to show that this premise is wrong. Order—a functioning whole—can be generated as well without controlling every inch of the relevant behaviour of living entities, since they can make this order themselves.

Clearly, the animals do not do this for this particular *purpose*, or with any intention to serve the whole. It is therefore possible that order generated from recursive control mechanisms is detrimental to our goals. That is why considerably slackening the reins is necessary, but most of the time even not sufficient to have this kind of synergy. The circumstances for this to happen have to be established. In the examples above, it's primarily the physical structuring of the animal house that makes the difference. Surely, structures like the aviary and the functionally divided sow animal house are genuine technical artefacts, designed and engineered in much the same way as the cages and crates. They are only differently structured, where the proportion between unidirectional and recursive control mechanisms, and the presence and quantity of slack, are differentiating characteristics.

The latter approach thus is not less *technical* than the first, but is more *technological* in the sense that it mixes technical and nontechnical ordering mechanisms in a deliberate and planned way. It therefore is at least as knowledge-intensive as the technical approach, but this knowledge derives from a wider diversity of disciplines, ranging from mechanical engineering to ethology.

The two design approaches differ also in the way in which they deal with complexity. In the cages and crates approach, complexity is reduced by breakdown of the whole into many identical subunits (cages/crates). The inputs and outputs of these subunits are made highly predictable by a number of unidirectional control measures until a black box results. After this, the inner workings are of no real interest anymore, so we can subsequently focus on dealing with the input and output streams of a collection of these subunits.

This particular strategy of complexity reduction cannot be achieved in the case of the aviary and group housing system. The basic unit here is the animal house itself, or—in the case of the aviary—a large part of it. Since these units consist of a multiple of entities and animals, much more has to be done within these units to have the whole to function in a reliable and predictable way. As long as we do not choose to radically redesign the animals themselves—to make them remotely controllable for instance—an approach like this forces us to pay considerable attention to the functioning of the whole in relation to its constituents. Or in other words: design or description of the system in terms of its components alone (animals as well as material constructions) would neglect important aspects of the whole that are responsible for its proper functioning, like for instance social aspects and the functional division of the animal house. Adopting this latter approach thus implies an increased focus on the system level compared to the cages and crates approach.

In current debates about animal welfare, the rights of animals to exhibit their natural repertoire of behaviour is stressed. More often than not, this right is seen as a constraint on and even an impairment of production objectives. At the very least, the examples discussed above show how system goals can be compatible with increased possibilities for the animals to exhibit a range of behaviours and to interact with each other socially. But our claim is stronger than that, since we argue that human goals for these systems, like reduction of emission, can be attained by productively engaging animal behaviour in the maintenance of a specified and planned order. Thus, instead of thinking that animal welfare is an additional societal requirement for the design of livestock systems that is technically in conflict with other—for example economical or ecological—requirements, we propose a design approach in which animal behaviour is taken as an integral part of the functioning of livestock systems. To a considerable extent, the currently perceived conflicts between animal welfare and production goals can then be softened or even eliminated.

Designing new systems for livestock production thus requires a change of perspective on how these systems are organized, and calls for a different kind of heuristics and problem solving strategies. A systematic methodology is still to be worked out, but we believe there is a lot of practical experience that can be used and analysed, both inside and outside established circles of technological research and development. One could think, for a start, of the following recommendations:

1. Identify what potential ordering mechanisms are already present in the behavioural repertoire of the animals involved.
2. Identify the social ordering mechanisms this species exhibits under ‘natural’ circumstances.
3. Take particular needs and pleasures of animals as a starting point.
4. Identify the range of adaptive responses these animals possess in relation to specific system parameters that matter to them, like feed and water input, temperature, climate, waste, construction and floor materials.
5. Investigate for each function in a system whether it could be realised without a controlling instance or artefact.
6. Look for possibilities to integrate functions into one structure or component.
7. Identify possible ordering relationships (like symbiosis or mutualism) with other living entities, like men, other species, bacteria, viruses, etc.

Although we have focused in the present paper on systems with one single species of animal, it is quite imaginable to think of systems in which more species live together. By using groups of different animals, or assemblies of animals and particular plants, we might further extend the approach of realising synergy between recursive and unidirectional control mechanisms.

References

Aarnink, A.J.A., 1997. Ammonia emission from houses for growing pigs as affected by pen design, indoor climate and behaviour. PhD thesis. Wageningen University, The Netherlands.

Beck, U., 1997. The reinvention of politics. Rethinking Modernity in the Global Social Order. Polity Press, Cambridge.

Blokhuis, H.J., Metz, J.H.M., 1995. Aviary housing for laying hens. IMAG, Wageningen, The Netherlands. Report 95-31, 196 pp.

Canh, T.T., 1998. Ammonia emission from excreta of growing-finishing pigs as affected by dietary composition. PhD thesis. Wageningen University, The Netherlands.

Feenberg, A., 1999. Questioning Technology. Routledge, London.

Groenestein, C.M., 2000. Welfare-friendly housing and ammonia emission. Pig Progress 16 (3), 27–28.

Groot Koerkamp, P.W.G., 1998. Ammonia emission from aviary housing systems for laying hens—inventory, characteristics and solutions. PhD thesis. Wageningen University, The Netherlands. 161 pp.

Groot Koerkamp, P.W.G., Keen, A., van Niekerk, Th.G.C.M., Smit, S., 1995. The effect of manure and litter handling and indoor climatic conditions on ammonia emissions from a battery cage and an aviary housing system for laying hens. Netherlands Journal of Agricultural Science 43, 351–373.

Hol, J.M.G., and Groot Koerkamp, P.W.G., 1999. Onderzoek naar de ammoniakemissie van stallen XLVI-Rondloopstal voor dragende zeugen met voerstation en strobed (Walking around house for pregnant sows with feeding station and straw bed). IMAG Wageningen, The Netherlands. Report 99-08, in Dutch.

Hughes, T., 1987. The evolution of large technological systems. In: Bijker, W.E., Hughes, T.P., Pinch, T.J. (Eds.), The Social Construction of Technological Systems—New Directions in the Sociology and History of Technology. The MIT Press, Cambridge (MA), pp. 51–82.

Infomil, 2002. LA04 regelgeving. Handreiking Ammoniak en Veehouderij (in Dutch). The Hague, The Netherlands. 86 pp.

Ketelaar-de Lauwere, C.C., Luttik, J., de Greef, K.H., Groot Koerkamp, P.W.G., Langeveld, J.W.A., Backus, G.B.C., 2000. Kentering en toekomst in de veehouderij (Turning-Point and Future in Livestock Farming). WUR, Wageningen, The Netherlands. In Dutch and English, 24 pp.

Latour, B., 1987. Science in Action: How to Follow Scientists and Engineers Through Society. Harvard Univ. Press, Cambridge (Mass.).

Latour, B., 1993. We Have Never Been Modern. Harvester Wheatsheaf, New York.

Lawrence, A.B., Appleby, M.C., Macleod, H.A., 1988. Measuring hunger in the pig using operant conditioning: the effect of food restriction. Animal Production 47, 131–137.

Ogink, N.W.M., Aarnink, A.A., Hoofs, A.I.J., Vermeij, I., 2001. Sustainable pig production with the Hercules-system. Proceedings Tagung Construction, Engineering and Environment in Livestock Farming, University of Hohenheim, Hohenheim, Stuttgart, Germany, 6–7 March, 326–331.

Simondon, G., 1958 and 1989. Du mode d'existence des objets technique. Aubier, Paris.

Sliggers, J. (Ed.), 2001. Op weg naar duurzame niveaus voor gezondheid en natuur. Overzichtspublicatie thema verzuring en grootschalige luchtverontreiniging. Report VROM 010344/h/10-01 17529/187, Ministerie van Volksgezondheid, Ruimtelijke Ordening en Milieubeheer (VROM). The Hague, The Netherlands. 229 pp.

Steiger, A., Tschanz, B., Jakob, P., Scholl, E., 1979. Verhaltungsuntersuchungen bei Mastschweinen auf verschiedenen Bodenbelagen und bei verschiedener Besatzdichte. Schweizer Archiv für Tierheilkunde 121, 109–126 (in German).