Robust performance: principles and potential applications in livestock production systems

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Abstract

In livestock production systems (LPS), the predominant strategy to maintain functionality is to control variation in the production environment by controlling internal system conditions and keeping away disturbances and perturbations. We may need to reconsider the way in which LPS are designed and function from the perspective of controlling variation. The aim of the present study was to identify strategies that can be applied in LPS to maintain the system's functionality in a dynamic environment. LPS are complex systems with natural, technical and social sub-systems. We therefore first explored these system fields by means of a literature study. On the basis of the strategies in each of the system fields, we developed a conceptual framework for robust strategies in the complex LPS. Robustness involves two aspects, resistance and flexibility. A system with a highly controlled environment has become resistant to certain perturbations, as they no longer influence the system's performance. Therefore, an optimal performance strategy can be used for this situation. This involves (1) uniformity and homogeneity, (2) efficiency and (3) enlarging of scale in the design of the system. Reducing the consequences in the presence of the perturbations minimizes the impact of external systems conditions on the performance of the system. This requires the system to change its mode of operation in a flexible way as a robust performance strategy. This strategy involves the rate of (1) diversity and heterogeneity, (2) redundancy and (3) a modular design, which determine the flexibility and ability to adapt to new circumstances. This paper shows that robustness, especially for any complex system including a biological subsystem, can be defined as the combination of resistance and flexibility. It is also shown that this definition fits best in designing a robust LPS.

Keywords: functionality, variation, resistance, flexibility

Introduction

Since World War II food policies in Europe focused on higher agricultural production output, low food prices and high food quality. Farmers responded with scaling up and intensification, through investment in capital and knowledge, specialization, mechanization and efficiency. As a consequence, livestock production systems (LPS) were able to improve production and product quality significantly, backed by governance measures and enhanced technologies (Frouws, 1998). The specialized context for LPS to produce to the maximal technical opportunities is created by control mechanisms that are needed to create a context that does not exceed the acceptable range of variation. Unintended and negative effects of this development are becoming critical to the acceptability of LPS. The current way of housing and managing animals has not only proved to increase vulnerability to outbreaks of diseases, but also evoked broad societal concerns about welfare of farm animals and environmental impact (Steinfeld *et al.,* 2006). This has fuelled the demand for more sustainable and robust livestock production systems. To reduce the negative impacts of livestock production, the pursuit of system characteristics of robustness might be considered as an alternative to the ongoing specialization and intensification cycle.

Although much research is carried out on the controversy of the definitions of sustainability and robustness, for example by Tilman *et al. (*2002) and Jen (2003), respectively, the concepts continue to be subject to discussion and redefining. Both do somehow express the need for the long term vitality of (livestock production) systems. Fresco (1992) distinguished four components of sustainability; (1) production, (2) efficiency, (3) stability and (4) resilience. The first two components, production and efficiency, are parameters that express the functioning of the system. The third and fourth components, stability and resilience, are system's properties that refer to the maintenance of functionality in changing conditions and the systems behavior inbehaviour on the long term.

As we will elaborate in later sections we associate robustness with the stability and resilience components in the definition by Fresco. We define stability as resistance of a system against perturbations. An important notion in our discussion is the distinction between the inner and outer system. The inner system is an organization of natural phenomena capable of attaining the goals in a range of environments. The outer system is the context in which the inner system operates. It determines the conditions for goal attainment (Simon, 1996). The inner system is in other words the examined system within a demarcation and can be defined on many levels; farm, chain or regional level etc. When we focus on a system at farm level, the farm (inner system) is the organization of ecological, social-economical en technical components (animals, household, management, animal housing etc.) that is capable of attaining its goals in a range of environments; the context in which the farm operates.

Resistance requires a set of system properties which minimizes the impact of perturbations to the inner system. Resistance is achieved by controlling, monitoring and intervening, which is done in the outer system. In this way the system has a smaller range of environments to cope with. In addition to resistance, we define resilience as the ability of the system to absorb and manage perturbations; a system may be temporarily affected by a perturbation but has the intrinsic ability to recover.

The aim of the present paper is to identify the range of strategies that can be applied in LPS design, to maintain the system's functionality in a dynamic context. Our hypothesis is that design of modern LPS is predominantly aimed at improvement of stability or resistance of systems, and that the ability to address changing circumstances can be increased through resilience or flexibility is insufficiently recognized and utilized, resulting in suboptimal robustness. Later in this paper we will explain the need for more flexibility in LPS.

Robustness as a sum of resistance and flexibility

Discussions of robustness inevitably require clarification of the definition for robustness as there is not a uniform concept. Jen (2005) summarized the general view of a forum on robustness as robustness being a term that captures our intuitive sense of one of the key determinants of long-term success or failure. Robustness is in our perspective the maintenance of functionality and Kitano's definition (Kitano, 2002) is therefore very useful. He defined robustness as the maintenance of specific functionalities of the system against perturbations.

As stated in the introduction, robustness can be achieved by resistance and flexibility (Table 1). Together resistance -*the withstanding and tolerance of perturbations*- and flexibility -*the ability and freedom of action to react and adapt or being adjusted when exposed to perturbations*- are two different system characteristics that enable the system to address the impact of perturbations on the systems performance and make up the robustness of the system. This leads towards the following theorem (Equation 1)

$$\text{Robustness} = \text{Resistance} + \text{Flexibility} \quad (1)$$

The more a system is designed with a focus on flexibility, the less perturbations will have an effect on the functioning of that system. However, flexibility is the backup for the lack of resistance; when resistance is not sufficient, the flexibility of the system can absorb the perturbation. The definition of robustness is often mixed with the definition of resilience. A clear distinction is made by Holling (1986) who stated that ecological resilience is concerned with a stability domain. The state or functionality of natural systems is not specified, as long as the system functions in a stable range and can recover within a non-specified time scale. In production systems however, there are specific production and efficiency targets that have to be met; a particular equilibrium state instead of a stability domain. Engineered resilience is present in designed and controlled systems. Our view is that engineering resilience does mainly rely on resistance, whereas ecological resilience is founded on an intrinsic ability to adapt to a changing environment.

Variation management in modern European LPS

In modern Western LPS that are focussed on efficient production with high output volumes, the predominant strategy to maintain functionality has been maintaining stability by minimizing perturbations. This is achieved by controlling variation in input conditions and keeping away disturbances. Controlling variation in modern Western LPS requires high input levels of technology and organization. For example, specialization towards one specific animal product on a farm or in a region is common. As a result no other product group is left to be exploited when the net revenues for a certain product diminish or when a disease breaks out. Therefore agricultural commodity

Table 1. Flexibility and resistance compared.

	Resistance	Flexibility
Definition:	Outer system can withstand and tolerate perturbations; no action of inner system needed	Inner system has the ability and freedom of action to react and adapt or being adjusted when exposed to perturbations
Ability to react to perturbations given by:	Outer system	Inner system
Variation:	Reduces variation to inner system	Reduces variation within inner system
Consequence:	System maintains specific functionalities against perturbations	

prices are controlled by financial or quota structures, and governments will interfere when trade is threatened by an infectious disease that affects the specialized production system. Also at farm level diseases are prevented by applying premedication and biosecurity for sources of disease. Continuous controlling, monitoring and intervention are needed to manage variation in the current LPS.

A different approach is found in agricultural systems where there is limited access to technologies to control or intervene, like in agricultural systems that apply organic farming practices because they cannot rely on pesticides, artificial fertilizer and antibiotics, or in many extensive farming systems in the developing world being dependent on climatic conditions and soil fertility. To maintain functionality in these systems, the systems have to rely upon intrinsic flexibility as the number of options to control the outer system is limited. To prevent high losses in these systems, less specialization is found and risk is spread over different product groups.

The intrinsic opportunities of a system are often not considered in Western LPS when a system faces a problem. The technological answer to the problem is in most cases an obvious solution and the possibilities to apply these are present in the capital and knowledge intensive systems. New problems that arise from resolving difficulties are succeeded by new technology-based solutions. However, a more holistic approach of tackling problems is frequently not applied, and a proactive integrated system design is often lacking.

We conclude that as a consequence of the dominant technological view on problem solving in LPS, the livestock production sector is mainly focused on improving resistance of its systems. Examples of the resistance strategy in European LPS are climate-controlled stables, quota systems, biosecurity measures or governmental interventions for controlling the outbreak of diseases. Flexibility in the inner environment is needed to cope with the variation that is still affecting the system. Although livestock production systems do have an intrinsic capacity to adapt to new circumstances, these characteristics are often not utilized.

The complexity of livestock production systems

Livestock production systems are complex, non-homogenous systems, meaning that boundaries of the system have to be defined carefully and a diversity of entities and relations within the boundaries exist. The system within the boundaries (*inner system*) is complex, and so is the context where the system is functioning in (*the outer system*). Complex dynamic systems emerge from their components and their relations and cannot be described by simple models (Cumming, 2005). Different hierarchical levels exist and within those levels there are biological, technical and socio-economic structures. The functionality of LPS is judged on various (ecological, economic en social) aspects of the output. Next to the different hierarchical element and aspect subsystems, we need to consider the functions of the system and specify the spatial and time scale of interest. LPS are engineered, i.e. designed and controlled, but do have ecological and social components like animals, crops, soils and people. These components are flexible and have the ability to adapt to a changing environment. The extent to which human influence is involved in complex systems, determines the rate of technical control in biological systems.

Presence or absence of robustness at one level does not imply presence or absence at another level (Jen, 2003). We cannot assume an animal production system to be robust when only the production animals are robust. A system approach requires focusing on all subsystem levels to obtain robustness. Overall robustness is determined to a large part by the interplay among redundancy of components, diversity that allows system level change, and modularity (Webb and Levin, 2005). Aiming for a system structure with this interplay of components, will lead to a different performance strategy, which is explained later in this section. LPS do also involve interactions in social-technical, in

social-biological, as well as in technological biological relations. Moreover, there is a social-technical-biological component present, which makes these systems more complex than other system structures. Additional to this, LPS are multifunctional on different levels, different time scales, and different regions, which make LPS even more complex.
For example, robustness on herd level in a dairy herd implies a robust inner system in the herd and so requires less control from the farm manager with respect to herd performance. On a higher scale, a dairy farm can be robust and needs less control from its outer system. A dairy farm context is regulated by its government policies. A poultry farm can have a time horizon of decades for its investments, whereas on a layer hen level a time horizon of months is more appropriate. Besides, a set-up for a robust pig farm in Europe may not work in Asia.

Two strategies for performance

To get a grip on robustness in LPS, first a closer look can be given to a system that contains mainly a social, natural or technical structure. Identifying the fundamental characteristics of variation management in simple systems assists to identify the core aspects of robustness. In general, two objectives in system design can be distinguished; we call these *optimized performance* design and *robust performance* design. In general, the optimized performance strategy is characterized by a short term view on performance and one where everything – including the outer system – can be controlled. The robust performance strategy focuses on the long term continuity strategy and less on short term success, and this strategy anticipates unforeseen events. The general notion of robust performance in control theory, is that the internal stability and performance of a specified system should not hold for only the plant (inner system) used for the design, but for all plants in a certain set (Doyle *et al.,* 1992). This means that the active control system is considered to be robust when it is able to manage with a range of inner systems.
As mentioned earlier, is overall robustness determined by the interplay between diversity, redundancy and modularity, and a higher extent of this interplay leads to more flexibility of the system. Handling perturbations involves adaptation, which subsequently involves change. Flexibility is determining the adaptive capabilities of the system. The push for more scale enlargement, specialization and efficiency is in conflict with the basic factors that determine the resilience of ecological systems. From Table 2, three characteristics of systems with a robust performance are given; the first characteristic is *diversity and heterogeneity*. Being more diverse and heterogenic demands the system to be more general. Generalization secures basic functionality and protect from system failure (Kubisch *et al.,* 2006). Systems with a more diverse set of elements and relations are more flexible. This flexibility provides the system with the ability to function, but in an alternative manner than the system was set initially. Secondly, the characteristic *redundancy* is based on over-dimensioning and back-up in the system. When the context cannot be optimally controlled, and thus the system is appealed to use its adaptability, redundancy is used to utilize built-in reserves. The third characteristic for robust performance in systems is *modularity*, thus a greater number of smaller units instead of a few big units. Due to segmentation or aggregation, systems are more divided in several independent units. A system is capable of generalization but also of specialization, both are mandatory to reach a mission's objective. The specialization process is essential for improving the performance. Efficiency refers to the way production factors or inputs are combined to produce outputs (Fresco, 1992).
Figure 1 is a clear example of Kitano about robustness (Kitano, 2007) and shows that when the system is designed for an optimized performance, it functions in a more specific context. Still, if the system is designed for robust performance, it functions in a broader context or a dynamic

Table 2. Framework for robust and optimized performance.

Robust performance		Optimized performance	
Objective:	Max. robustness	Objective:	Max. performance
Constraint:	Performance > minimal performance	Constraint:	Robustness > minimal robustness
Characteristics:	Strategy:	Characteristics:	Strategy:
Diversity and heterogeneity	Generalization	Uniformity and homogeneity	Specialization
Redundancy	Over dimensioning Back-up	Efficiency	Tailoring Fitting
Modularity	Segmentation Aggregation	Unity	Merging Unification

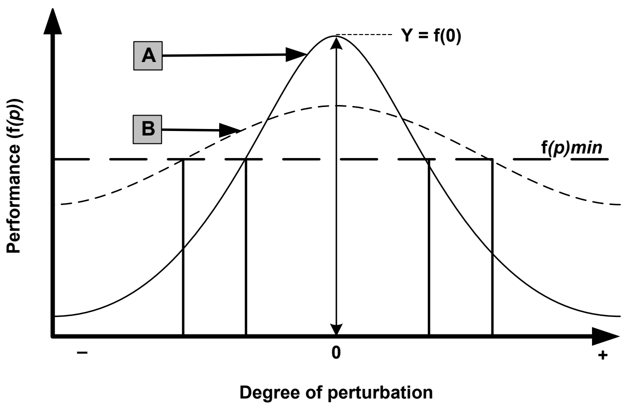

Figure 1. On a continuum between robust and optimized performance, system B is closer to robust performance than system A is.

environment. In this example, system B in the figure has a lower optimal performance but it has a higher tolerance for the degree of perturbation than system A. System B does meet the minimal performance, *f(p)min*, in a wider range of environments, thus is the most robust of the two systems. System A has a high performance in an optimal environment, but a lower tolerance for the degree of perturbation. To maintain a good performance, system A requires a better controlled environment. Robustness is essential for (biological) systems, however costs increase (Csete and Doyle, 2002; Kitano, 2002). Applying redundancy, modularity and diversity requires more resources for the inner system, than in the most efficient situation. A more flexible system lowers the need for controlling the context, so the resources needed for the outer system are reduced.

Optimal or robust performance strategies in livestock production systems

We wish to explain that the framework also covers LPS. In 2006, Ten Napel *et al.* (2006) proposed a distinction between the control model and the adaptation model. In the control model:

- the system is protected from exposure to disturbances as much as possible;
- is the balance maintained by design dependent on monitoring and intervention;
- implicitly is assumed that new problems or demands can be solved with add-on solutions.

The control model assumes that by continuous monitoring and controlling the system, build-in regulation is sufficient to keep the system in the preferred state. This can be related to the resistance part of robustness, whereas the adaption model:

- allows the systems to cope where possible, but protects them where necessary;
- utilizes intrinsic adaptation mechanisms and allows them to learn-by-doing and support them;
- considers the possibility that fundamental re-design may be necessary.

Therefore, the adaption model uses the assumption that the system has the adaptive ability to move towards the preferred stated while exposed to perturbations, and making more use of the flexibility part of robustness. The adaption model is common in biological systems, technical systems are more strongly based on the control model, but both types of systems are using the same three basic strategies, namely the interplay of modularity, redundancy and diversity to reach a stable state.
As an example, the optimal temperature at a pig farm can be for the whole barn and to control this optimal temperature, the barn is insulated and is equipped with a thermostat and heating system. This strategy aims on a stable environment in the pens without fluctuations or differences in temperature. But this strategy does also neglect the intrinsic ability of the systems. If different climate zones in a pen are present and the pig has the freedom to move around, it can decide itself what the optimal climate is. This latter situation needs flexibility of the inner system and less control of the environment.
The choice is not exclusively between the optimal performance strategy and the robust performance strategy. For a certain LPS, it is dependent to what extent its subsystems are balanced between both strategies, as its characteristics are on a continuum between being solely optimal or robust driven. But while making choices, it is preferable to choose a (sub)system design option on this continuum that tends towards robust performance. This robust performance design will gain flexibility in the LPS and subsequently this will lower the need for control. Finally, the robust performance strategy will give LPS the potential of increased abilities while dealing with changing circumstances.

Conclusion

This paper shows that robustness, especially for complex system including a biological subsystem, can be defined as the combination of resistance and flexibility. It is also shown that this definition best fits future designing for robust LPS, and that aiming at a robust performance includes strategies that are in conflict with those for the optimal performance strategy.

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